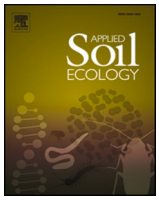
Applied Soil Ecology 190 (2023) 105014

Contents lists available at ScienceDirect

Applied Soil Ecology

journal homepage: www.elsevier.com/locate/apsoil



# Soil enzymatic activity in Brazilian biomes under native vegetation and contrasting cropping and management

Julierme Zimmer Barbosa [a,*], Giovana Poggere [b], Rodrigo Studart Corrêa [c], Mariangela Hungria [d], Ieda de Carvalho Mendes [e]

[a] Federal Institute of Southeast of Minas Gerais, Barbacena, Minas Gerais 36205-018, Brazil
[b] Federal Technological University of Paraná, Medianeira, Paraná 85884-000, Brazil
[c] University of Brasília (FUP/UnB), Planaltina, Distrito Federal 73340-710, Brazil
[d] Embrapa Soja, P.O. Box 4006, Londrina, Paraná 86085-981, Brazil
[e] Embrapa Cerrados, P.O. Box 08223, Planaltina, Distrito Federal 73310-970, Brazil

ARTICLE INFO

*Keywords:*
Land use
Soil quality
Non-tillage system
Integrated crop-livestock
Biological indicators
Nutrient cycling

ABSTRACT

Enzymatic activity is a useful indicator for the evaluation of soil biological components. However, a detailed analysis of such indicators in Brazilian soils is lacking. In this study, the activity of soil enzymes was evaluated using data from 73 publications covering 57 locations across all six biomes and eight soil orders out of the 13 that occur in Brazil. The results indicated a wide variation of enzymatic activity in soils, where the means in μg p-nitrophenol $g^{-1}$ soil $h^{-1}$ were 569, 116, 112, and 80 for acid phosphatase, alkaline phosphatase, β-glucosidase, and arylsulfatase, respectively. Likewise, values of 148 μg reducing sugars $g^{-1}$ soil $day^{-1}$ for cellulase, 57 μg triphenyl tetrazolium formazan $g^{-1}$ soil $day^{-1}$ for dehydrogenase, and 38 μg N-$NH_4^+$ $g^{-1}$ soil $h^{-1}$ for urease were recorded. Soil organic matter and microbial biomass were the best attributes correlated with enzymatic activity, followed by clay content and pH. A more detailed analysis of the acid phosphatase, arylsulfatase, and β-glucosidase activities showed that land-use effects were more pronounced in the Atlantic Forest and Cerrado than in the Caatinga biome. Soils under non-tillage and integrated crop-livestock systems showed higher enzymatic activity than soils under conventional tillage. Soils housing higher biodiversity and delivering higher crop yields also presented higher enzymatic activity, especially in terms of arylsulfatase and β-glucosidase. Enzymatic activity has been shown to be a versatile indicator of soil quality, as it can elucidate how to achieve high-quality standards in tropical and subtropical soils.

## 1. Introduction

Several indicators have been used to study the nature and properties of soils. In recent decades, increased attention has been paid to biological indicators. This is directly related to the recognition of the importance of understanding soil ecosystems, which requires the integration of different indicators to assess soil quality (Resende et al., 2019; Creamer et al., 2022). Among these indicators, enzymatic activity provides useful information that can enhance our understanding of soil ecosystems, particularly soil functions related to nutrient cycling and plant production. This is because soil enzymes catalyze the hydrolytic and oxidative reactions associated with the decomposition of organic compounds (ligninases, cellulases, proteases, glycosidases, and galactosidases) and nutrient mineralization (phosphatases, sulfatases, and ureases) (Burns et al., 2013).

Soil enzyme activity is sensitive enough to capture changes in soils due to different land use and management practices (Bandick and Dick, 1999; Balota et al., 2004; Mendes et al., 2019a, b; Naves et al., 2020; Anghinoni et al., 2021; Poggere et al., 2022), which are associated with soil environmental variations in the biotic and abiotic components of enzymatic activity. Edaphic organisms, such as microorganisms and plants, are the primary sources of soil enzymes that synthesize and excrete them. After the death of organisms, intracellular enzymes are released upon plasma membrane rupture, and they can accumulate in the soil owing to the formation of complexes with organic and/or mineral soil fractions. However, most methods used to determine soil enzyme activity capture the sum of the activities of living organisms (biotic components) and extracellular enzymes accumulated in soils

* Corresponding author.
*E-mail addresses:* barbosajz@yahoo.com.br, julierme.barbosa@ifsudestemg.edu.br (J.Z. Barbosa).

https://doi.org/10.1016/j.apsoil.2023.105014
Received 7 July 2022; Received in revised form 8 June 2023; Accepted 11 June 2023
Available online 16 June 2023
0929-1393/© 2023 Elsevier B.V. All rights reserved.

(abiotic components) (Wallenstein and Burns, 2011).

Brazil is one of the main producers of food, fiber, and energy worldwide (FAOSTAT, 2020), and approximately 60 % of its native vegetation cover is preserved (MapBiomas, 2020). This is related to the development of science-based tropical agriculture, which allows high crop productivity using fewer fertilizers and pesticides (Parra, 2014; EY Brasil/CropLife, 2021; Barbosa et al., 2022a; Hungria et al., 2022), while also considering soil conservation (Polidoro et al., 2021). The country has also a long tradition of analyzing soil enzymes. The first articles on this subject were published in 1982 (Kulinska et al., 1982; Melo et al., 1982), and studies on soil enzymes have increased since 2010 (Balota et al., 2013; Sobucki et al., 2021). The last and most successful example of such a development has been the launching of the soil bioanalysis technology, SoilBio (BioAS in Portuguese, Bioanálise do Solo), a pioneering initiative based on the inclusion of arylsulfatase and β-glucosidase analysis as part of routine soil analysis for on-farm soil quality assessment (Mendes et al., 2021a; Mendes et al., 2021b).

The evaluation of enzymatic activity in Brazilian soils has revealed a set of important aspects related to the conversion of native vegetation into agroecosystems and the impacts of soil conservation practices in tropical and subtropical environments (Nogueira et al., 2006; Peixoto et al., 2010; Lopes et al., 2013; Lopes et al., 2015; Notaro et al., 2018; Mendes et al., 2019a; Carlos et al., 2021). In this sense, it is possible to highlight the wide adoption of non-tillage (NT) systems that provide better soil quality when compared to conventional tillage systems (CT), where intense soil disturbance occurs (Balota et al., 2004; Kaschuk et al., 2011; Mendes et al., 2019a; Anghinoni et al., 2021). Nevertheless, studies on the effects of land-use change considering different enzymes and native vegetation across the six terrestrial Brazilian biomes are scarce. Additionally, there are extensive areas under pastures in the country, most of which have experienced some degree of degradation (Feltran-Barbieri and Féres, 2021). To reduce pasture degradation and promote sustainable production intensification, the adoption of integrated production systems has increased over the past 10 years (Skorupa and Manzatto, 2019; Anghinoni and Vezzani, 2021; Valani et al., 2021), and there have been contrasting results regarding soil enzymatic activity (Costa et al., 2018; Zago et al., 2019; Cunha et al., 2021).

A national-scale assessment of soil enzymatic activity that considers edaphoclimatic, biological, and agricultural diversity (Vilela et al., 2019; Alba et al., 2021; Barbosa et al., 2021; Barbosa et al., 2022b; Caballero et al., 2022) can contribute to increasing knowledge of the natural variability of enzymatic activity across Brazilian soils and clarify the potential of each enzyme as an indicator of the best conservation practices to promote soil quality. Based on such a scenario, we hypothesized that there are differences in soil enzymatic activity depending on the biome, land use, and soil management. Considering this hypothesis, this study aimed: (*i*) to identify patterns of enzymatic activity in soils of the Brazilian biomes; (*ii*) to evaluate the impact of land use on soil enzymatic activity for different biomes.

## 2. Material and methods

### 2.1. Brief description of Brazilian biomes

Brazil has six terrestrial biomes, the main characteristics of which are described below.

The Amazon biome extends mainly to the northern region of Brazil in addition to parts of the central-west and northeast regions, covering approximately 49.3 % of the country. The Amazonian climate is tropical with an annual mean temperature of 25 °C and 2300 mm/year of rainfall. Most of the biome is covered with evergreen tropical forests, followed by other areas with lowland and savannah vegetation (Vilela et al., 2019). Artificial landscapes are spread over 15 % of the biome and consist mainly of pastures (88 %) and agricultural land (11 %) (MapBiomas, 2020). Ferralsol and Acrisol soils occur in uplands and have low natural fertility, whereas in the lowlands, highly fertile Gleysol soils are predominant (Schaefer et al., 2017).

The Atlantic Forest extends across the south, southeast, central-west, and northeast regions of Brazil, covering 13 % of the country. It has different environmental characteristics, and its climate varies from tropical to subtropical, thereby allowing the development of tropical and subtropical forests (Vilela et al., 2019). The area occupied by human activity is equivalent to 64 % of the biome and is represented by pastures (39 %) and agricultural land (29 %) (MapBiomas, 2020). Despite the high variability in the soil order, Ferralsol and Acrisol soils prevail in this biome (Coelho et al., 2017).

The Caatinga biome mainly occurs in the northeastern region of Brazil and in some parts of the southeastern region of the state of Minas Gerais, accounting for approximately 9.7 % of the country. This biome mostly presents conditions of high temperature and low rainfall owing to its semi-arid tropical climate, with a predominance of xerophytic vegetation in different strata (trees, shrubs, and herbaceous plants) (Vilela et al., 2019). Most (65 %) of the biome is covered by native vegetation. Human activity accounts for 35 % of the biome (pasture 63 %, multiple land uses 31 %) (MapBiomas, 2020). Arenosols and Regosols are the most abundant soil classes in the biome, followed by Ferralsols, Acrisols, and Luvisols. Commonly, soils are characterized by the presence of salts and an alkaline pH (Araújo Filho et al., 2017).

The Cerrado is the second largest biome in Brazil after the Amazon. It spreads to 24 % of the country over its central-west, southeast, north, and northeast regions. Seasonal tropical climates are predominantly characterized by dry winters and rainy summers (Vilela et al., 2019). The vegetation is diversified and classified into savannah, forest, and grassland formations, which cover 53 % of the biome. Anthropic landscapes, which cover 45 % of the biome, are represented by pastures (52 %) and agriculture (28 %) (MapBiomas, 2020). The soils are chemically poor and vary in texture, especially Ferralsol ones (Oliveira et al., 2017).

The Pampas occurs in 2.1 % of the country's territory in the southern region of Brazil. The climate is humid subtropical, with cold winters, warm summers, an annual mean temperature of 18.3 °C, and 1534 mm/year of rainfall (Vilela et al., 2019). The native vegetation is mainly represented by herbaceous plant species, such as grasses, which cover 55 % of the biome. The areas under anthropogenic influence are mostly used for agriculture (86 %) (MapBiomas, 2020). On flat plateaus, the main soil classes (Leptosol, Vertisol, Chernozem, and Planosol) are generally fertile, while Arenosol and Ferralsol soils are present in this biome (Almeida, 2017).

The Pantanal biome is located in the central-west region of Brazil and covers 1.8 % of the country. Its climate is tropical with dry winters and rainy summers; the annual mean temperature is 25 °C and the annual mean precipitation is 1200 mm/year. The native vegetation is diverse, ranging from forest and savannah formations on the uplands to large areas of flooded fields (Vilela et al., 2019). Only 16 % of the area is engaged in anthropic activities that are entirely represented by pastures (MapBiomas, 2020). The soils originated from sedimentary rocks, with a predominance of low-fertility sandy soils. The formation processes of most soils in this biome are strongly associated with hydromorphism, with a greater presence of Planosol, Gleysol, Plinthosol, Podzol, and Arenosol soils (Couto et al., 2017).

### 2.2. Data compilation

A systematic search for publications that evaluated the enzymatic activity in Brazilian soils was conducted on the Web of Science and Google Scholar platforms until December 2022. The following combinations of terms were used in the search: soil, enzymatic activity, enzymes, Brazil, Brazilian, Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas, and Pantanal. Publications regarding the surveyed soil layer, pretreatment of soil samples, and the method used for enzymatic activity analysis were reviewed. We standardized the values of these variables according to the highest frequency of use in the literature. Each surveyed publication was scrutinized to determine whether the study met the

following criteria: (1) conducted in Brazil; (2) soil samples collected from the 0–10 cm depth layer; (3) soil samples analyzed under field moisture conditions; (4) results that could be extracted directly from the text, tables, and figures. Further selection criteria were applied to these publications regarding the methods of analysis of acid phosphatase (EC 3.1.3.2), alkaline phosphatase (EC 3.1.3.1), arylsulfatase (EC 3.1.6.1), β-glucosidase (EC 3.2.1.21), cellulase (EC 3.2.1.4), dehydrogenase (EC 1.1.1), and urease (EC 3.5.1.5). Only publications that employed the following methods of enzymatic analysis were selected: acid phosphatase and alkaline phosphatase (Eivazi and Tabatabai, 1977; Tabatabai, 1994); arylsulfatase (Tabatabai and Bremner, 1970; Tabatabai, 1994); β-glucosidase (Eivazi and Tabatabai, 1988; Tabatabai, 1994); cellulase (Schinner and Von Mersi, 1990); dehydrogenase (Casida et al., 1964); urease (Tabatabai and Bremner, 1972; Tabatabai, 1994). Seventy-three publications, which covered 57 Brazilian locations, were selected (Fig. 1; Table S1).

### 2.3. Data extraction and preparation

The mean activity values of acid phosphatase, alkaline phosphatase, arylsulfatase, β-glucosidase, cellulase, dehydrogenase, and urease were manually extracted from publications and transferred to a spreadsheet. In addition, information on the studied areas and their soil attributes were also extracted: city, state, soil order, biome, land use, management system, time under NT system, soil clay content, soil pH ($H_2O$), soil available P concentration (Mehlich 1 extractor), soil bulk density, soil organic matter (SOM) content, soil organic C (SOC) content, microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), extraction efficiency factors of C ($K_C$) and N ($K_N$), index of soil biological diversity, and crop yield. The variability in soil clay and SOM content and other soil attributes analyzed in this study are presented in Fig. 2 and Fig. S1, respectively.

SOC was converted to SOM using a correction factor of 1.724. For the analysis of MBC and MBN, only data obtained by the fumigation-extraction (FE) method were used (Brookes et al., 1985; Vance et al., 1987), with the aim of data standardization, because this was the most used method in the studies found. Owing to the variations in the $K_C$ and $K_N$ values, the MBC and MBN data were corrected such that all values were expressed with the same extraction efficiency factors, with $K_C$ of 0.40 (Roscoe et al., 2006) and $K_N$ of 0.54 (Brookes et al., 1985).

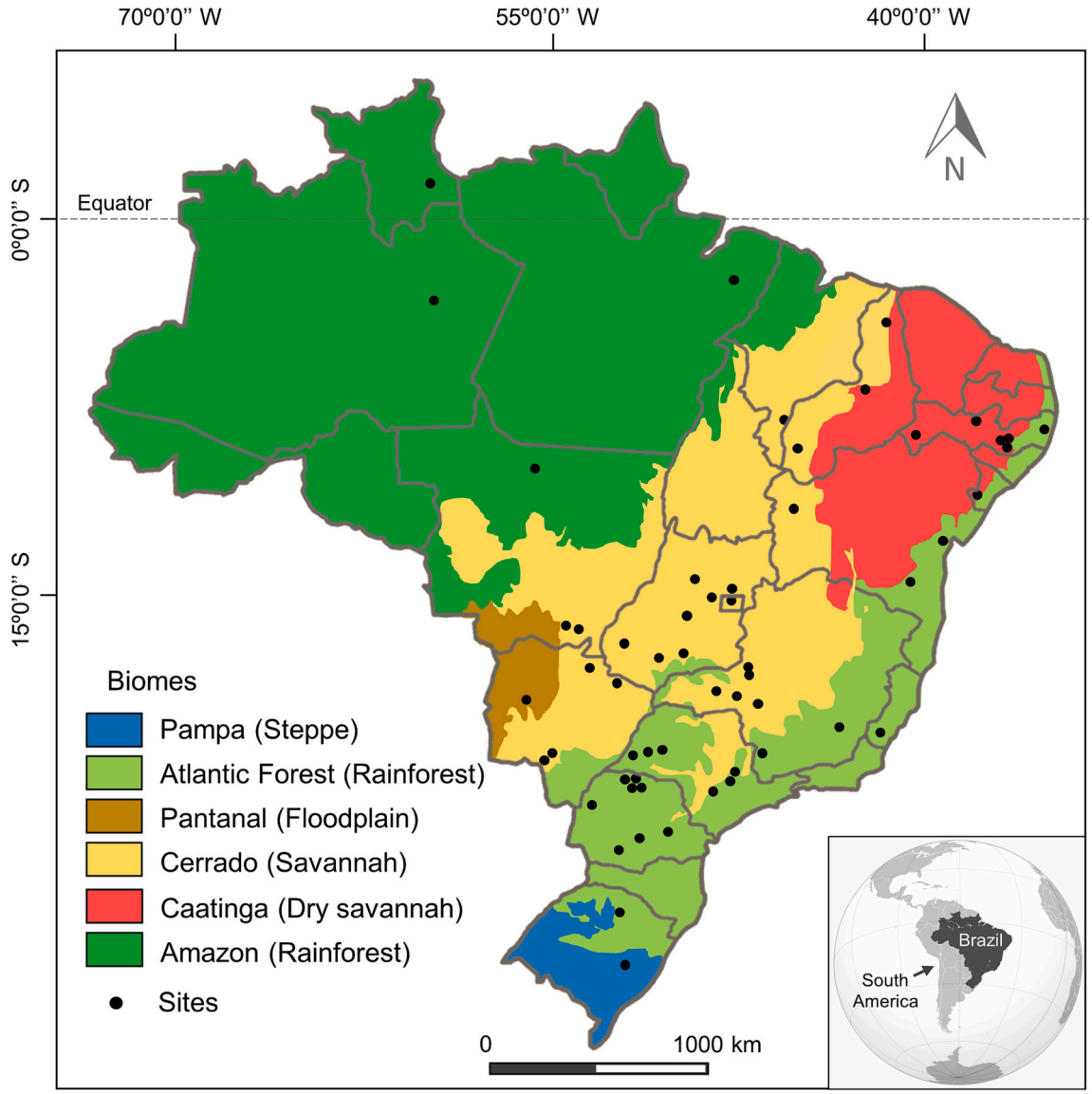



**Fig. 1.** Brazilian locations ($n$ = 57) corresponding to 73 publications used to compose this study.

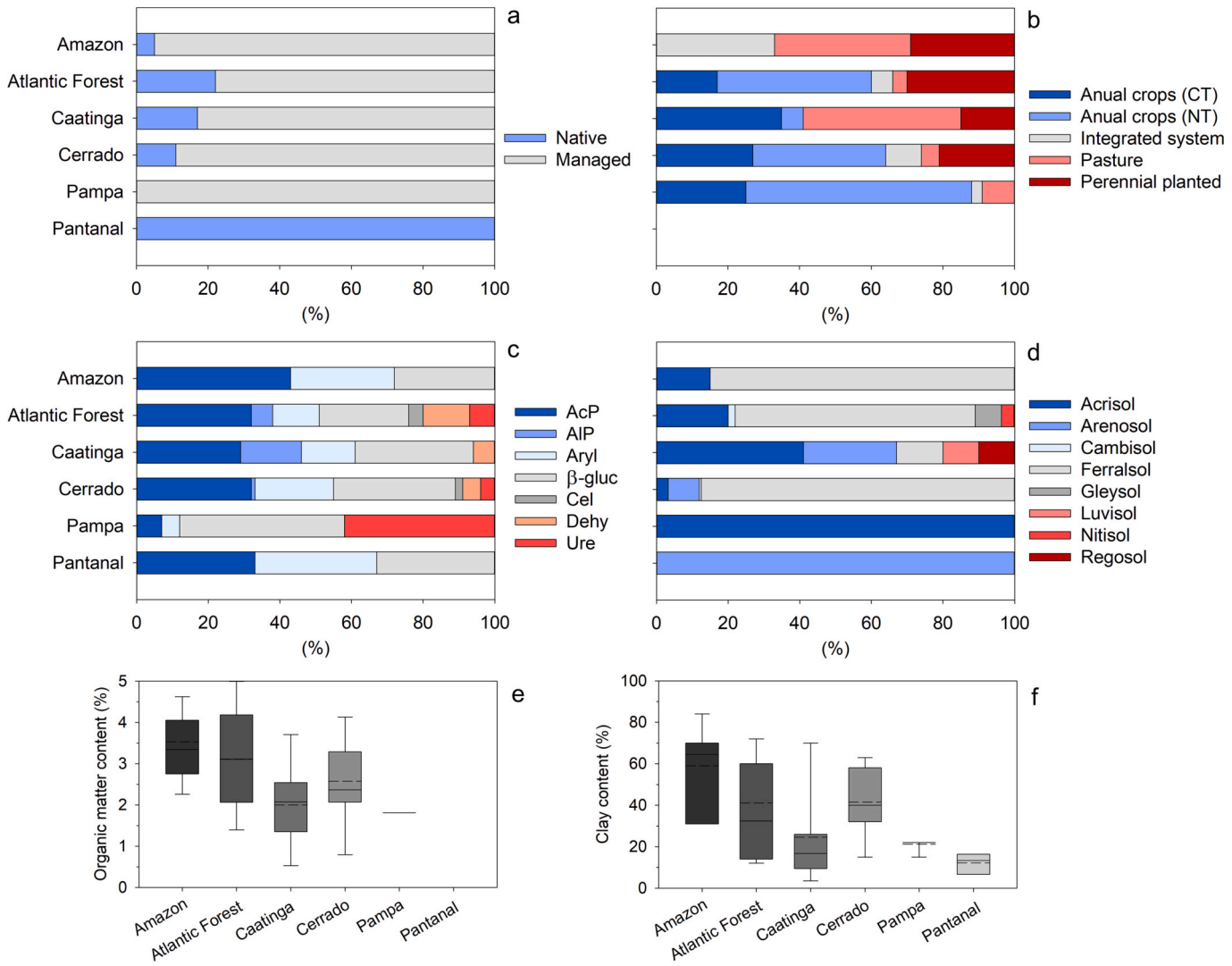



**Fig. 2.** Soil samples used in the analysis, according to (a) land use; (b) crop management; (c) enzyme in each biome; (d) soil order; (e) organic matter content; (f) clay content. AcP = acid phosphatase; AlP = alkaline phosphatase; Aryl = arylsulfatase; β-gluc = β-glucosidase; Cell = cellulase; = Dehy = dehydrogenase; Ure = urease.

### 2.4. Data analysis

Soil enzymatic activity can vary according to several factors (e.g., vegetation, climate, and soil); therefore, in this study, we categorized the data by biome, which incorporates the main variations associated with vegetation and climate. However, the data were obtained from the 0–10 cm soil layer, which has little or no importance in soil classification at order level. Hence, these attributes respond better to vegetation, soil use, and topsoil management.

Descriptive statistical analysis was initially performed to summarize the data on soil enzymatic activity for the entire country and separately for each biome. This analysis covered measures of central tendency (mean and median), measures of variability (standard deviation, minimum, maximum, and coefficient of variation), and the number of soil samples. The relationship between soil attributes and enzymatic activity was analyzed by Pearson's correlation analysis using the entire dataset. Only groups with >10 samples were analyzed, and correlations were considered significant at $p < 0.05$.

The effects of land use on the activities of acid phosphatase, arylsulfatase, and β-glucosidase were evaluated by comparing the four different land uses with the highest percentages of soil samples in the Atlantic Forest, Caatinga, and Cerrado biomes (Fig. 2). Other land uses and enzymes were not evaluated owing to the low number of samples.

The effect of the adoption time of the NT system was evaluated by comparing three periods in the soils of the Cerrado (<5, 6–15, and >16–23 years), and two periods in the Atlantic Forest (15–19 and 20–25 years). As the data from these groups (land use and time under NT) did not present a normal distribution or homogeneous variances, non-parametric tests were adopted for the comparisons. The Mann-Whitney *U* test was used to analyze whether the two groups of data. The Kruskal-Wallis test was used for the same purpose when three or more groups were compared, and the means were compared using the Dunn test.

It was not possible to perform a statistical analysis to assess the effects of integrated production systems on soil enzyme activity, or to associate enzymatic activity to soil biodiversity and crop yield. Therefore, we obtained the mean, minimum, and maximum values of enzymatic activity in soils under integrated production systems and control conditions based on the publications used in our research. To provide an overview of the relationships between crop yield, biodiversity, and enzymatic activity, we considered both the worst scenario of crop yield or soil biodiversity and the best scenario, obtaining the percentage difference between these scenarios for enzymatic activity. All analyses were performed using the Statistica software.

## 3. Results

Acid phosphatase, alkaline phosphatase, arylsulfatase, β-glucosidase, cellulase, dehydrogenase, and urease showed high variation in their activity among soils across the Brazilian biomes (Table 1). Differences were evident among soils from the Atlantic Forest, Cerrado, and Caatinga biomes. Acid phosphatase presented the highest mean values when soils from all biomes were grouped, except in the Caatinga, where soils presented low acid phosphatase activity and high alkaline phosphatase activity. Soils from the Atlantic Forest biome showed the highest mean values of β-glucosidase, cellulase, and urease activity.

Soil organic matter (SOM), microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN) were the attributes most related to enzymatic activity and were positively correlated with acid phosphatase, arylsulfatase, β-glucosidase, cellulase, and dehydrogenase (Fig. 3). Soil clay contents positively correlated with acid phosphatase, arylsulfatase, and β-glucosidase activities. The low number of samples may have impaired the correlation analysis between clay content and dehydrogenase and urease activities, whereas it was not possible to perform the analysis of cellulase activity because $n < 10$. In contrast, the pH positively correlated with alkaline phosphatase and negatively correlated with acid phosphatase and cellulase. Likewise, phosphorus concentrations positively correlated with urease and β-glucosidase, and negatively correlated with alkaline phosphatase (Fig. 3).

The conversion of natural ecosystems to agroecosystems influenced soil enzyme activity only in the Atlantic Forest and Cerrado biomes (Fig. 4). In both biomes, acid phosphatase activity was higher in soils under native vegetation cover than in soils under other land use types. However, the β-glucosidase activity was similar in soils under native vegetation and annual cropping under NT systems in the Atlantic Forest, whereas the same enzyme showed less activity in soils under native Cerrado vegetation cover than in soils cultivated with annual crops under NT.

Significant differences were observed between agroecosystems with contrasting soil managements in the Atlantic Forest and Cerrado biomes, especially in soils cultivated with annual crops (Fig. 4). Soils with annual crops under NT showed higher acid phosphatase, arylsulfatase, and β-glucosidase activities than those under CT, except for acid phosphatase in the Atlantic Forest biome. However, the activity of these three enzymes increased with the time of adoption of the NT system in Cerrado Ferralsols, but only for arylsulfatase in Atlantic Forest Ferralsols (Fig. 5).

Higher values of acid phosphatase, arylsulfatase, and β-glucosidase activities were observed in soils under integrated crop-livestock (ICL) than in soils under NT systems, especially during the cropping phase (Fig. 6). Although the changes were less pronounced, increases in SOM content were recorded in soils under the ICL-cropping systems. In contrast, acid phosphatase, arylsulfatase, and β-glucosidase activities in the ICL-pasture systems were similar to or slightly higher than those recorded in soils under pastures.

Evaluations of the relationship between soil biodiversity and enzymatic activity showed that the acid phosphatase, β-glucosidase, and arylsulfatase activities were 13 %, 25 %, and 60 % higher, respectively, in soils with higher microbial diversity (Table 2). Acid phosphatase was the enzyme with the highest occurrence in these soils when a decrease in enzymatic activity was detected in soils with high biodiversity. Considering the relationship between crop yield and soil enzyme activity, the acid phosphatase (+33 %), β-glucosidase (+94 %), and arylsulfatase (+331 %) activities presented higher mean values in soils from agricultural sites with high crop yields (Table 3).

**Table 1**
Descriptive analysis [mean, standard deviation (SD), minimum, maximum, median values, and coefficient of variation (CV)] of acid phosphatase, alkaline phosphatase, arylsulfatase, β-glucosidase, cellulase, dehydrogenase, and urease activity values in soils (0–10 cm layer) of the Brazilian biomes.

| Biome | Mean | SD | Min | Max | Median | CV (%) | n[a] |
|---|---|---|---|---|---|---|---|
| | Acid phosphatase (μg p-nitrophenol $g^{-1}$ soil $h^{-1}$) | | | | | | |
| All | 569 | 451 | 0.7 | 2644 | 431 | 79 | 478 |
| Amazon | 786 | 856 | 47 | 2644 | 230 | 108 | 21 |
| Atlantic Forest | 517 | 296 | 34 | 1500 | 430 | 57 | 199 |
| Caatinga | 190 | 310 | 0.7 | 1110 | 29 | 163 | 40 |
| Cerrado | 678 | 493 | 100 | 2595 | 549 | 73 | 212 |
| Pampa | 241 | 118 | 140 | 430 | 243 | 49 | 5 |
| Pantanal | 274 | 151 | 127 | 430 | 266 | 55 | 3 |
| | Alkaline phosphatase (μg p-nitrophenol $g^{-1}$ soil $h^{-1}$) | | | | | | |
| All | 116 | 78 | 0.9 | 450 | 105 | 67 | 64 |
| Atlantic Forest | 90 | 44 | 18 | 183 | 87 | 49 | 37 |
| Caatinga | 155 | 106 | 0.9 | 450 | 181 | 68 | 23 |
| Cerrado | 132 | 28 | 105 | 172 | 126 | 22 | 4 |
| | Arylsulfatase (μg p-nitrophenol $g^{-1}$ soil $h^{-1}$) | | | | | | |
| All | 80 | 83 | 0.3 | 457 | 49 | 103 | 266 |
| Amazon | 56 | 30 | 35 | 135 | 49 | 54 | 10 |
| Atlantic Forest | 53 | 72 | 5 | 350 | 23 | 135 | 87 |
| Caatinga | 16 | 10 | 0.3 | 38 | 13 | 65 | 20 |
| Cerrado | 106 | 87 | 6 | 457 | 86 | 82 | 144 |
| Pampa | 175 | 45 | 143 | 227 | 156 | 25 | 3 |
| Pantanal | 140 | 76 | 83 | 227 | 111 | 55 | 3 |
| | β-glucosidase (μg p-nitrophenol $g^{-1}$ soil $h^{-1}$) | | | | | | |
| All | 112 | 140 | 4 | 2206 | 78 | 127 | 474 |
| Amazon | 53 | 52 | 9 | 191 | 39 | 98 | 16 |
| Atlantic Forest | 159 | 224 | 5 | 2206 | 102 | 141 | 155 |
| Caatinga | 91 | 84 | 4 | 528 | 66 | 93 | 45 |
| Cerrado | 95 | 67 | 12 | 356 | 68 | 71 | 226 |
| Pampa | 64 | 31 | 18 | 152 | 61 | 49 | 31 |
| Pantanal | 106 | 27 | 78 | 132 | 109 | 25 | 3 |
| | Cellulase (μg reducing sugars $g^{-1}$ soil $day^{-1}$) | | | | | | |
| All | 148 | 151 | 0.2 | 620 | 120 | 102 | 39 |
| Atlantic Forest | 264 | 170 | 106 | 620 | 205 | 65 | 16 |
| Cerrado | 68 | 58 | 0.2 | 160 | 70 | 85 | 23 |
| | Dehydrogenase (μg triphenyl tetrazolium formazan $g^{-1}$ soil $day^{-1}$) | | | | | | |
| All | 57 | 61 | 1.0 | 350 | 40 | 107 | 121 |
| Atlantic Forest | 52 | 50 | 1 | 197 | 35 | 96 | 80 |
| Caatinga | 133 | 135 | 12 | 350 | 72 | 102 | 9 |
| Cerrado | 47 | 36 | 1 | 115 | 49 | 76 | 32 |
| | Urease (μg $N\text{-}NH_4^+$ $g^{-1}$ soil $h^{-1}$) | | | | | | |
| All | 38 | 48 | 0.8 | 258 | 14 | 127 | 99 |
| Atlantic Forest | 78 | 51 | 14 | 258 | 70 | 66 | 42 |
| Cerrado | 8 | 7 | 0.8 | 23 | 5 | 94 | 29 |
| Pampa | 9 | 3 | 3 | 15 | 9 | 36 | 28 |

[a] n denotes the number of samples used for descriptive analysis.

## 4. Discussion

### 4.1. Overview of the enzymatic activity of Brazilian soils

Soil, climate, vegetation, and agroecosystem characteristics are sharply contrasting across Brazil (Vilela et al., 2019; Alba et al., 2021; Barbosa et al., 2021; Caballero et al., 2022) and there is correspondingly high variability in soil enzymatic activity (Table 1). This variability can be understood through the relationships among soil attributes and abiotic and biotic components of enzymes (Wallenstein and Burns, 2011), as observed in global (Sinsabaugh et al., 2008; Margalef et al., 2017) and national scale studies (Talbot et al., 2014; Acosta-Martínez et al., 2021). The intensities of alkaline phosphatase, arylsulfatase, and β-glucosidase activities compiled in this study for Brazilian soils were similar to those reported in the USA (Acosta-Martínez et al., 2021). However, higher values of acid phosphatase activity were observed in the soils of the Amazon, Atlantic Forest, and Cerrado than in the USA soils, probably because of the very acidic characteristics of Brazilian soils.

The close relationship among $H^+$ activity, SOM, clay content, and

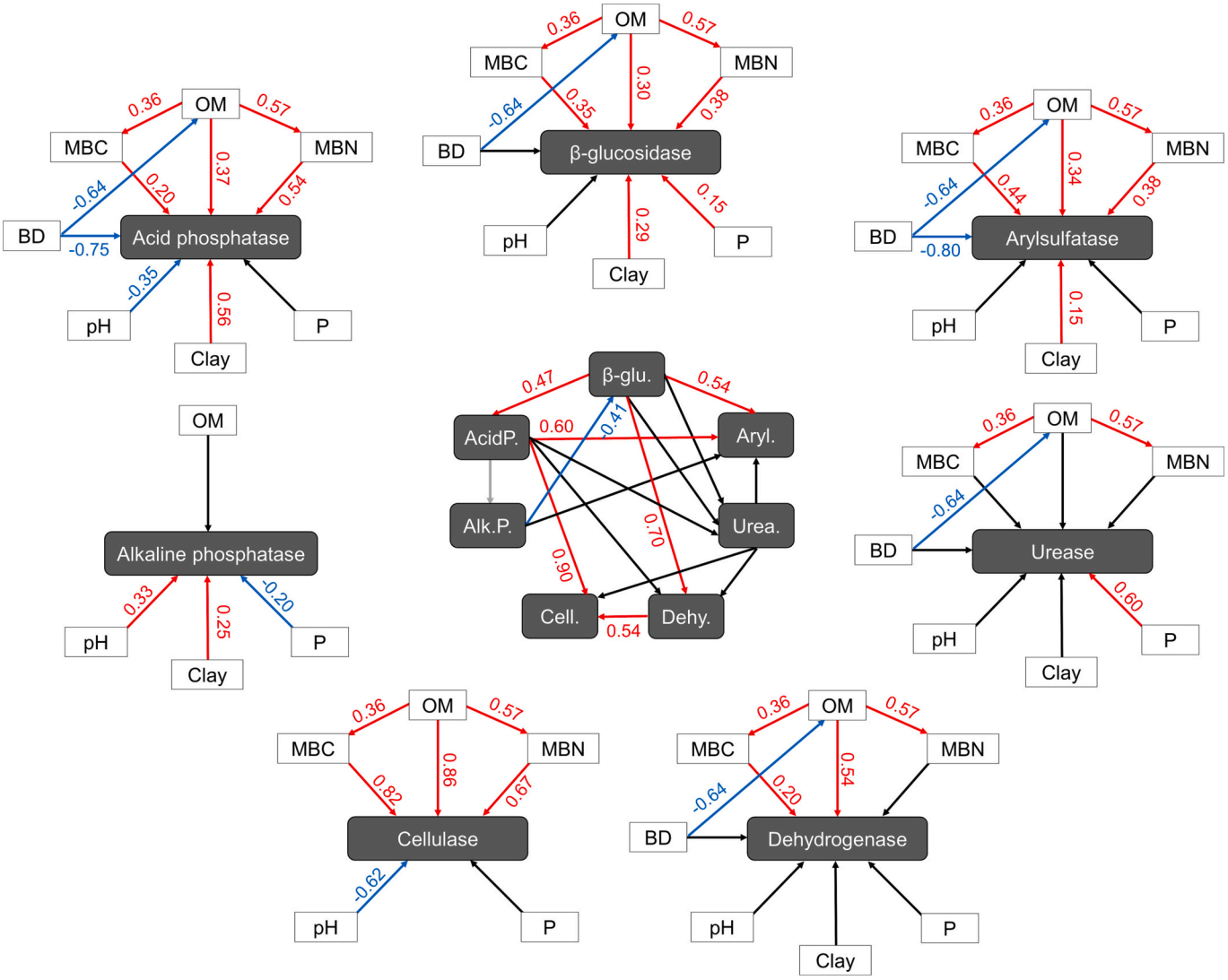



**Fig. 3.** Correlations among acid phosphatase, arylsulfatase, alkaline phosphatase, β-glucosidase, cellulase, dehydrogenase, urease activity and other soil attributes at 0–10 cm layer. Red and blue arrows indicate significant either positive or negative correlations ($p < 0.05$), while black arrows indicate no significant correlation ($p > 0.05$). Values associated with arrows indicate the Pearson correlation coefficient. The absence of a box associated with an attribute indicates that it was not possible to perform the correlation ($n < 10$). SOM – soil organic matter; MBC – microbial biomass carbon; MBN – microbial biomass nitrogen; BD – bulk density; P – available phosphorus; Clay – clay content. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

acid phosphatase activity (Tabatabai, 1994; Zhao et al., 2012; Paul et al., 2022) ensures the Brazilian biomes discrimination, especially Caatinga soils in relation to soils from other biomes (Table 1). Despite alkaline phosphatase activity can also be affected by SOM, $H^+$ activity, and clay contents (Spohn and Kuzyakov, 2013), its outstanding activity in Caatinga soils (Table 1, Fig. 3) suggest greater importance of lower soil $H^+$ activity. Available inorganic P is another key factor for the activity of soil phosphatases (Tabatabai, 1994). However, the relationship between P availability and phosphatases activities may not be clearly evidenced (Fig. 3) as it presents a dual effect (Tabatabai, 1994), especially in studies with large soil databases (Tan et al., 2014; Margalef et al., 2017). Very low soil concentrations of available inorganic P can severely limit phosphatase activity owing to unsatisfactory plant growth and reduced SOM incorporation (Lopes et al., 2013), and increased P availability may favor phosphatases activities by increasing SOM and P organic forms. Those conditions without limitation by SOM incorporation related to P, an increase in the soil available inorganic P suppressed phosphatase activity owing to lower demand for organic P acquisition (Spiers and McGill, 1979; Mori, 2022).

Enzymes that play a key role on the carbon cycle are very sensitive to variations in SOM and microbial biomass (Burns et al., 2013; Mariscal-Sancho et al., 2018; Sobucki et al., 2021), and contribute to the capacity of β-glucosidase and cellulase in discriminate Atlantic Forest SOM-rich soils (Table 1). These soil attributes are equally important for determining the activity of enzymes involved in the cycle of other elements, such as urease in the N cycle (Tabatabai, 1994; Sobucki et al., 2021). However, higher urease activity in Atlantic Forest soils has been associated with production systems that evaluated cover crops (Balota and Chaves, 2010; Cordeiro et al., 2021), which may be due to the release of urease from plant residues or stimulation of the production by microorganisms (Nivelle et al., 2016; Adetunji et al., 2021).

### 4.2. *Effect of the conversion of natural ecosystems to agroecosystems*

Changes in land use from native vegetation to farmland have altered the quantity and quality of plant residues and agricultural inputs entering the soil environment beyond soil disturbance, thus affecting soil attributes (Nogueira et al., 2006; Lanna et al., 2010; Kaschuk et al., 2011; Lopes et al., 2013; Barcellos et al., 2015; Notaro et al., 2018; Peng et al., 2021). A decrease in the SOM content and limestone application

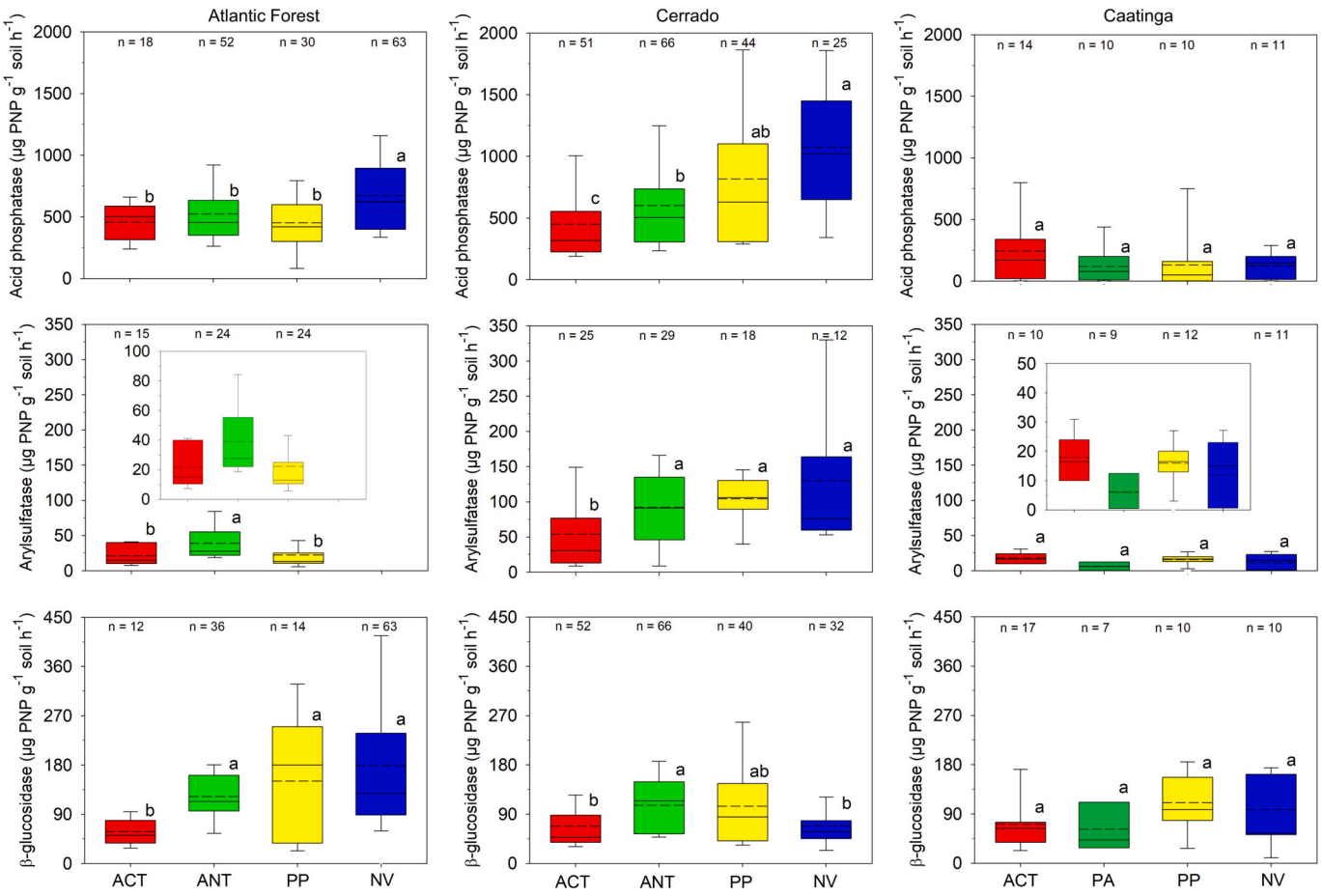

Atlantic Forest
Cerrado
Caatinga
Acid phosphatase (µg PNP g$^{-1}$ soil h$^{-1}$)
Arylsulfatase (µg PNP g$^{-1}$ soil h$^{-1}$)
β-glucosidase (µg PNP g$^{-1}$ soil h$^{-1}$)
n = 18 n = 52 n = 30 n = 63
n = 51 n = 66 n = 44 n = 25
n = 14 n = 10 n = 10 n = 11
n = 15 n = 24 n = 24
n = 25 n = 29 n = 18 n = 12
n = 10 n = 9 n = 12 n = 11
n = 12 n = 36 n = 14 n = 63
n = 52 n = 66 n = 40 n = 32
n = 17 n = 7 n = 10 n = 10
ACT ANT PP NV
ACT ANT PP NV
ACT PA PP NV

**Fig. 4.** Effect of land use on acid phosphatase, arylsulfatase, and β-glucosidase (µg p-nitrophenol g$^{-1}$ soil h$^{-1}$) activity at 0–10 cm soil layer in the Cerrado, Caatinga, and Atlantic Forest biomes. Abbreviations indicate: ACT – annual crops under conventional tillage system; ANT – annual crops under non-tillage system; PP – perennial plants; PA – pasture; NV – native vegetation. The lower limit of boxes indicates the 25th percentile and the upper limit the 75th percentile; Bars below and above boxes indicate the 5th and 95th percentiles; lines inside the box mark the median (solid line) and mean (dashed line). Letters above the boxes indicate that the groups differ ($p < 0.05$).

has followed deforestation for farmland development (Nogueira et al., 2006; Souza et al., 2016; Peng et al., 2021), and acid phosphatase demonstrated higher sensitivity to this land use conversion (Fig. 4). In addition, the application of phosphate fertilizers to cultivated soils can contribute to a reduction in acid phosphatase activity under some conditions (Tabatabai, 1994). The effect of P fertilization on reducing phosphatase activity in soils has been more pronounced in tropical forests than in non-tropical ecosystems (Mori, 2022), highlighting the importance of soil enzymes in regulating primary productivity in the tropics (Bustamante et al., 2004; Peixoto et al., 2010; Lopes et al., 2018).

Even in soils with similar texture and organic matter contents, β-glucosidase activity is consistently lower in soils under native vegetation compared to that in cultivated soils under NT in the Cerrado biome (Peixoto et al., 2010; Lopes et al., 2013; Mendes et al., 2019a). This trend denotes a peculiarity of the biological functioning of Cerrado soils, as it has not been recorded in other Brazilian biomes or enzymes (Fig. 4) and may be related to the quantity and quality of plant residues that return to the soil. As β-glucosidase acts in the final step of cellulose decomposition (converting cellobiose into glucose molecules) (Tabatabai, 1994), its activity is lower for soils under woody native vegetation of Cerrado (Fig. 4), where plant residues are more complex than in NT cultivated areas (Mendes et al., 2019a). Cerrado physiognomies also play a major role in determining soil biological patterns (Mendes et al., 2012). Forest physiognomies (Mata de Galeria and Cerradão) presented the highest enzymatic activities compared to grassland (Campo Sujo) and savanna physiognomies (Cerrado Ralo and Cerrado sensu stricto).

There is great variability in enzymatic activity in the Caatinga soils (Medeiros et al., 2015; Notaro et al., 2018; Pedrotti et al., 2018; Silva et al., 2019; Costa et al., 2022), which may have contributed to the undetectable differences between soils under native vegetation and crops (Fig. 4). Caatinga soils are usually poor in clay and SOM content, and such characteristics have been reported to reduce the abiotic components of enzymes (Wallenstein and Burns, 2011), which is considered important for detecting differences arising from land use and soil management (Vinhal-Freitas et al., 2017; Mendes et al., 2019a; Lopes et al., 2021). Thus, the variability of enzymatic activity in Caatinga soils may be more influenced by short-term factors such as fertilization, crop season, and plant species.

### 4.3. *Effect of land uses and soil management in agroecosystems*

Plowing and harrowing in CT accelerate SOM mineralization, which may cause soil degradation, especially in tropical and subtropical regions such as Brazil (Didoné et al., 2019; Thomaz and Antoneli, 2022). In contrast, NT systems do not significantly disturb soils and increase the magnitude of flows of energy and matter and longer residence periods resulting from the non-linear relationships among mineral particles, organic compounds, plants and their roots, and organisms (Anghinoni and Vezzani, 2021). These differences ensure high enzymatic activity for soils under NT than CT (Fig. 4) as observed in very contrasting soil conditions in Brazil (Almeida, 2012; Torres et al., 2020; Carlos et al., 2021) and worldwide (Zuber and Villamil, 2016; Mirzavand et al.,

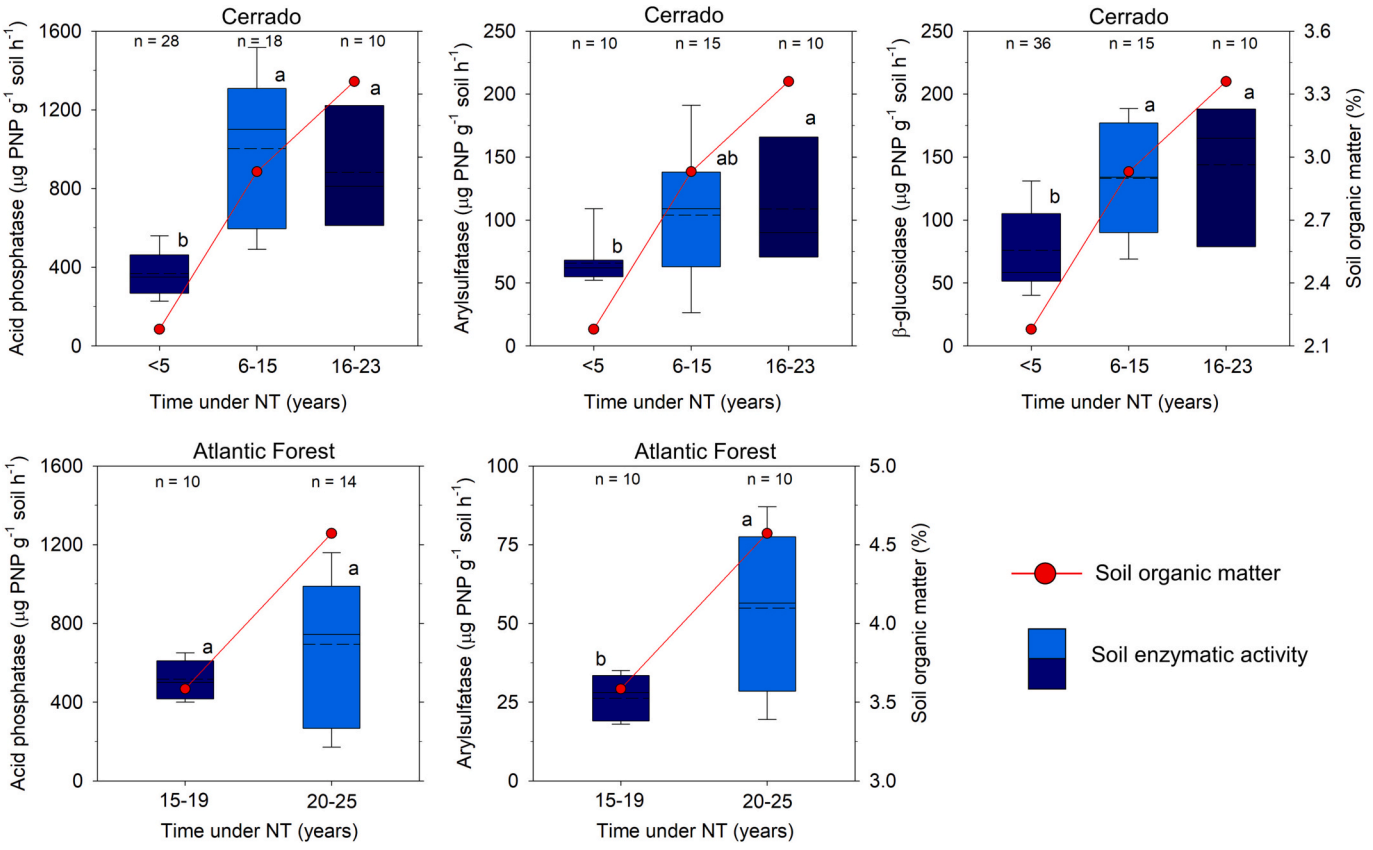



**Fig. 5.** Effect of time under non-tillage system (NT) on acid phosphatase, arylsulfatase, and β-glucosidase (μg p-nitrophenol $g^{-1}$ soil $h^{-1}$) activities and mean soil organic matter content at 0–10 cm Ferrosols' layer in the Cerrado and Atlantic Forest biomes. The lower limit of boxes indicates the 25th percentile and the upper limit the 75th percentile; bars below and above boxes indicate the 5th and 95th percentiles; lines inside the box mark the median (solid line) and mean (dashed line). The letters above the boxes indicate that the groups differ ($p < 0.05$).

2022). New states of self-organization are reached after extended periods under NT (Anghinoni and Vezzani, 2021), and the evolution of soil quality is marked by higher enzymatic activity and SOM contents (Fig. 5). However, several studies have shown that soil enzymes can better reflect changes in management practices than SOM (Bandick and Dick, 1999; Kandeler et al., 1999; Peixoto et al., 2010; Lopes et al., 2013; Mendes et al., 2019a). This ability to anticipate changes in soil quality and the relationship with crop yields (Table 3) favors the selection of arylsulfatase and β-glucosidase for soil bioanalysis (SoilBio technology) in Brazil (Mendes et al., 2021a; Mendes et al., 2021b). Yet, this study and the SoilBio technology highlighted the importance of high enzymatic activity in soils under NT for nutrient cycling (Guedes et al., 2020; Marafon et al., 2020; Mendes et al., 2019a; Mendes et al., 2021a) and soil biodiversity (Passinato et al., 2021).

Soils under NT for extended periods can still benefit by increasing crop diversity (Kaschuk et al., 2011; Almeida, 2012; Balota et al., 2014; Anghinoni et al., 2021) and applying raw organic residues (Table S2). These factors added to the effects of the animal component in the integrated crop-livestock (ICL) systems, which recycles the vegetative material and modifies the dynamics of nutrient cycling (Carvalho et al., 2010), favors soil microbiota and SOM (Mendes et al., 2019a; Franco et al., 2020; Sousa et al., 2020), contributing to increasing the soil enzymatic activity under ICL-cropping phase. However, divergent changes in soil enzymatic activity under ICL-pasture phase and pasture (Fig. 6) suggest the influence of different managements and conservation levels of pastures (Feltran-Barbieri and Féres, 2021) such a trend has also been detected in the integrated crop-livestock-forest (ICLF). The acid phosphatase, arylsulfatase, and β-glucosidase activities were higher in soils under the ICLF than in degraded pastures (Zago et al., 2019; Damian et al., 2021). No differences in acid phosphatase and β-glucosidase activities were detected between soils under the ICLF and well-managed pastures (Cunha et al., 2021). Thus, an integrated production system is an important strategy to improve soil quality in tropical and subtropical degraded pastures to ensure sustainable agriculture and livestock production intensification.

### 4.4. Limitations and future directions

Based on a limited understanding of enzymatic activity in Brazilian soils at the national scale, the present study has synthesized published information on the issue, providing new insights into the variations in soil enzymatic activity in different biomes, land uses, and soil managements, and its importance as an indicator of soil quality. However, the currently published databases and frameworks still have limitations that need to be overcome in future studies.

The selected studies sampled soils from different sites and seasons, and some statistical analyses were based on groups with variable numbers of samples and specific conditions that could not be analyzed separately (e.g., soil type, crop species, and fertilization). The influence of these factors on the soil enzymatic activity variation was probably smaller between biomes than among land-use types. There have been difficulties in standardizing the variation factors to evaluate soil enzymatic activity at a national scale. Thus, the methodological approach of the present study is understandable considering a large-scale analysis (Margalef et al., 2017; Zheng et al., 2018).

There are six biomes in Brazil, and we found a higher number of publications on the Atlantic Forest and Cerrado biomes (Fig. 1). Based on our results, there is a need to i) increase the number of studies for Amazon, Caatinga, Pampa, and Pantanal biomes, ii) increase the number of studies on integrated production systems, which are highly beneficial

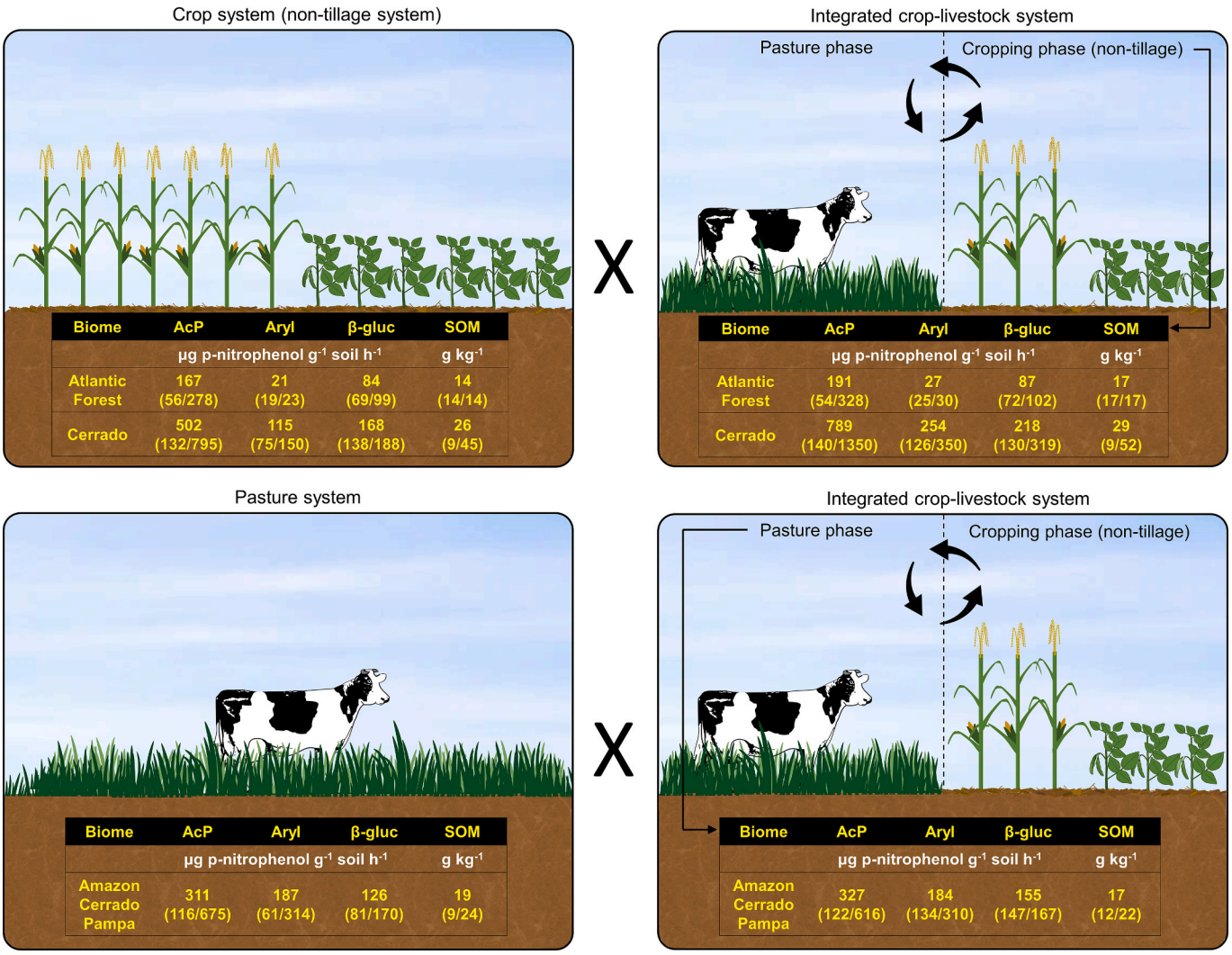

Crop system (non-tillage system)
Integrated crop-livestock system
Pasture phase
Cropping phase (non-tillage)
X
Biome | AcP | Aryl | β-gluc | SOM
µg p-nitrophenol g-1 soil h-1 | g kg-1
Atlantic Forest | 167 (56/278) | 21 (19/23) | 84 (69/99) | 14 (14/14)
Cerrado | 502 (132/795) | 115 (75/150) | 168 (138/188) | 26 (9/45)
Biome | AcP | Aryl | β-gluc | SOM
µg p-nitrophenol g-1 soil h-1 | g kg-1
Atlantic Forest | 191 (54/328) | 27 (25/30) | 87 (72/102) | 17 (17/17)
Cerrado | 789 (140/1350) | 254 (126/350) | 218 (130/319) | 29 (9/52)
Pasture system
Integrated crop-livestock system
Pasture phase
Cropping phase (non-tillage)
X
Biome | AcP | Aryl | β-gluc | SOM
µg p-nitrophenol g-1 soil h-1 | g kg-1
Amazon Cerrado Pampa | 311 (116/675) | 187 (61/314) | 126 (81/170) | 19 (9/24)
Biome | AcP | Aryl | β-gluc | SOM
µg p-nitrophenol g-1 soil h-1 | g kg-1
Amazon Cerrado Pampa | 327 (122/616) | 184 (134/310) | 155 (147/167) | 17 (12/22)

**Fig. 6.** Mean (minimum/maximum) values of acid phosphatase (AcP), arylsulfatase (Aryl), β-glucosidase (β-gluc), and organic matter (SOM) in the 0–10 cm layer of Brazilian soils under different cultivation systems. Crop systems and crop-livestock integration systems (cropping phase) information after Carneiro et al. (2009), Portilho et al. (2015), Mendes et al. (2019a), Santos (2020), and Soares (2021); Pasture systems and crop-livestock integration systems (pasture phase) information after Mendes et al. (2019a) and Damian et al. (2021).

to agricultural sustainability and iii) correlate the benefits of soil quality with economic and environmental aspects. Therefore, the universal adoption of standardized protocols across laboratories and regions is of utmost importance (Acosta-Martínez et al., 2021).

The recent inclusion of β-glucosidase and arylsulfatase has been routinely analyzed in Brazil (SoilBio technology) (Mendes et al., 2021b), and the increasing interest in soil enzymology will certainly contribute to building a larger and more robust dataset on soil enzymatic activity that can expand the knowledge on soil quality and its benefits for the ever-growing sustainability of tropical and subtropical agriculture.

## 5. Conclusion

The present study demonstrated that Brazilian soils have a wide range of enzymatic activities related to biomes and land uses. The Amazon, Atlantic Forest, and Cerrado biomes have soils with high acid phosphatase activity, whereas the soils of the Caatinga biome, poor in organic matter and clay content, and not very acidic, showed low acid phosphatase and arylsulfatase activities and high alkaline phosphatase activity.

Soil enzymatic activity is associated with the conversion of natural ecosystems into agroecosystems. Acid phosphatase can differentiate land use conversion in the Atlantic Forest and Cerrado biomes, with greater activity in soils under native vegetation. Arylsulfatase in Cerrado soils and β-glucosidase in Atlantic Forest soils only presented higher activity levels under native vegetation compared with agricultural soils under conventional tillage. However, β-glucosidase in Cerrado soils has unique characteristics, as its activity is low under native conditions, suggesting a strong influence of vegetation composition on its enzymatic activity.

Considering the agroecosystems in the Atlantic Forest and Cerrado biomes, it was found that soils under non-tillage systems had higher enzymatic activity than soils under conventional tillage systems. However, it has been possible to increase soil enzyme activity with the adoption of integrated crop-livestock systems. Furthermore, high enzymatic activity in soils housing high biodiversity and supporting high crop yields has been revealed, especially in terms of arylsulfatase and β-glucosidase activities. These findings contribute to a deeper understanding of the biological functionality of tropical and subtropical soils.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

**Table 2**
Variation in edaphic organisms' diversity and activity of acid phosphatase, arylsulfatase, and β-glucosidase in 0–10 cm layer of Brazilian soils at low and high diversity of a particular group of soil biota.

| Biome | Organism group | Low diversity[a] | | | | Variation at high diversity | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| | | D | AcP | Aryl | β-gluc | D | AcP | Aryl | β-gluc | |
| | | | μg p-nitrophenol $g^{-1}$ soil $h^{-1}$ | | | % | | | | |
| Amazon | Bacteria | 2.08 | 116 | 61 | 81 | +96 | +5 | +120 | +107 | Damian et al. (2021) |
| Atlantic Forest | Bacteria | 3.11 | 240 | 181 | 32 | +22 | +42 | +36 | +73 | Damian et al. (2021) |
| | Bacteria | 6.16 | 189 | nd | nd | +3 | -2 | nd | nd | Leite et al. (2021) |
| | AMF | 0.80 | 513 | nd | 48 | +75 | -19 | nd | +30 | Feiler (2020) |
| | AMF | 1.20 | 419 | nd | 66 | +33 | −6 | nd | -21 | Feiler (2020) |
| | AMF | 2.20 | 385 | nd | 39 | +36 | +33 | nd | +22 | Feiler (2020) |
| | AMF | 2.30 | 371 | nd | 52 | +35 | +5 | nd | +64 | Feiler (2020) |
| | AMF | 2.80 | 551 | nd | 86 | +29 | -18 | nd | +11 | Feiler (2020) |
| Caatinga | Bacteria | 6.25 | 116 | nd | 62 | +2 | -6 | nd | −13 | Costa et al. (2022) |
| | Microbial | 1.99 | 1.4 | 0.8 | 142 | +6 | −8 | −65 | −84 | Barros et al. (2020) |
| Cerrado | Bacteria | 3.80 | 674 | 76 | 62 | +11 | +64 | +180 | +29 | Pessoa-Filho et al. (2015) |
| | Bacteria | 3.60 | 360 | 135 | 47 | +31 | −69 | −53 | +38 | Bobul'ská et al. (2021) |
| | Microbial | 2.88 | 1203 | 42 | 45 | +3 | +46 | +148 | +34 | Ribeiro (2012) |
| Pampa | Bacteria | 2.88 | 142 | 142 | 129 | +14 | +71 | +9 | +18 | Damian et al. (2021) |
| Pantanal | Microbial | 3.01 | 265 | 111 | 78 | +1 | +62 | +104 | +38 | Pelissaro et al. (2020) |
| Mean values | | | | | | +26 | +13 | +60 | +25 | |

[a] Low and high diversities have considered the lowest and higher values of diversity in each study. AMF = Arbuscular mycorrhizal fungi; FAMEs = fatty acid methyl esters; D = value of ecological index, considering the Shannon diversity index; AcP = acid phosphatase; Aryl = arylsulfatase; β-gluc = β-glucosidase; nd = not determined.

**Table 3**
Variation of crop yield and acid phosphatase, arylsulfatase, and β-glucosidase activities in 0–10 cm of Brazilian soils compared to the best and the worst scenarios based on yield.

| Biome | Crop | Worst scenario[a] | | | | Variation at best scenario | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Yield | AcP | Aryl | β-gluc | Yield | AcP | Aryl | β-gluc | |
| | | t/ha | μg p-nitrophenol $g^{-1}$ soil $h^{-1}$ | | | (%) | | | | |
| Atlantic Forest | Cotton | 0.9 | nd | nd | 22 | +95 | nd | nd | +150 | Cordeiro et al. (2021) |
| | Cotton | 1.4 | nd | nd | 18 | +69 | nd | nd | +55 | Cordeiro et al. (2021) |
| | Maize | 3.9 | 394 | nd | 50 | +72 | −11 | nd | +1 | Durrer et al. (2021) |
| | Soybean | 2.0 | 425 | nd | 42 | +100 | 0 | nd | +147 | Firmano et al. (2021) |
| | Soybean | 1.8 | 40 | 19 | 79 | +33 | +55 | +27 | +48 | Soares (2021) |
| | Soybean | 2.7 | 310 | 23 | 72 | +8 | −16 | +1 | +5 | Soares (2021) |
| | Sugarcane | 26 | nd | nd | 28 | +15 | nd | nd | −18 | Tenelli et al. (2019) |
| | Wheat | 1.4 | 355 | nd | nd | +86 | −9 | nd | nd | Kuwano et al. (2017) |
| Cerrado | Avocado | 12.5 | 365 | 41 | 33 | +112 | −9 | −23 | +15 | Nacata (2021) |
| | Cotton | 5.2 | 221 | 6 | 45 | +12 | +7 | +100 | +13 | Lopes et al. (2021) |
| | Maize | 9.1 | 238 | 12 | 43 | +1 | +5 | −8 | +14 | Lopes et al. (2021) |
| | Soybean | 3.0 | 451 | nd | 132 | +66 | +26 | nd | +9 | Simon et al. (2019) |
| | Soybean | 3.6 | 221 | 10 | 37 | +37 | +14 | +50 | +68 | Lopes et al. (2021) |
| | Soybean | 3.0 | nd | nd | 30 | +40 | nd | nd | +116 | Anghinoni et al. (2021) |
| | Soybean | 4.0 | nd | 130 | 330 | +12 | nd | +38 | +24 | Pires et al. (2022) |
| | Soybean | 3.6 | nd | 61 | 103 | +6.7 | nd | +100 | +31 | Mendes et al. (2019c) |
| | Soybean | 3.7 | 589 | 28 | 64 | +4.9 | +71 | +696 | +264 | Mendes et al. (2019c) |
| | Maize+Soybean | 3.5 | 426 | 11 | 53 | +3642 | +227 | +1600 | +520 | Mendes et al. (2021b) |
| | Maize+Soybean | 62 | 846 | 58 | 161 | +108 | −14 | +77 | +8 | Mendes et al. (2021b) |
| | Maize+Soybean | 5.9 | 540 | 11 | 70 | +1766 | +116 | +1318 | +277 | Mendes et al. (2021b) |
| | Sugarcane | 66 | nd | nd | 20 | +39 | nd | nd | +133 | Tenelli et al. (2019) |
| Mean values | | | | | | +301 | +33 | +331 | +94 | |

[a] Worst and best scenarios have considered the treatments with lower and higher yield. AcP = acid phosphatase; Aryl = arylsulfatase; β-gluc = β-glucosidase; nd = not determined.

the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgments

J.Z. Barbosa acknowledge the Support Program for Research – Researcher Grant modality (grant # 23223.003631/2021-02) from the Federal Institute of Southeast of Minas Gerais. I.C. Mendes and M. Hungria, acknowledge a research fellowship from the CNPq. Partially financed by INCT - Plant-Growth Promoting Microorganisms for Agricultural Sustainability and Environmental Responsibility (CNPq 465133/2014-4, Fundação Araucária-STI 043/2019, CAPES), Brazilian Agricultural Research Corporation (Embrapa, projects 02.14.01.026.00 and 20.20.03.017.00), the National Council for Scientific and Technological Development (CNPq), Edital Universal (grant # 404764/2016-9), and by the Research Support Foundation of the Federal District (FAPDF), Edital Demanda Espontânea 2016 (grant # 1355/2016).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.apsoil.2023.105014.

## References


Acosta-Martínez, V., Pérez-Guzmán, L., Veum, K.S., Nunes, M.R., Dick, R.P., 2021. Metabolic activity–enzymes. In: Karlen, D.L., Stott, D.E., Mikha, M.M. (Eds.), Laboratory Methods for Soil Health Analysis, Soil Health Series, vol. 2. American Society of Agronomy, Madison, pp. 194–250.

Adetunji, A.T., Ncube, B., Meyer, A.H., Olatunji, O.S., Mulidzi, R., Lewu, F.B., 2021. Soil pH, nitrogen, phosphatase and urease activities in response to cover crop species, termination stage and termination method. Heliyon. 7, e05980 https://doi.org/10.1016/j.heliyon.2021.e05980.

Alba, M.I.M.D., Rodríguez, O.J.O., Osorio, L.P.O., Pinilla, I.D.V., 2021. Preliminary valuation of environmental importance of Brazilian sites, with regards to ecological and sociocultural axes. Ambient. Soc. 24 https://doi.org/10.1590/1809-4422asoc20200209r1vu2021L5AO.

Almeida, D.O., 2012. Fauna epiedáfica e atributos microbiológicos de solos sob sistemas de manejo no subtrópico brasileiro. Universidade Federal do Rio Grande do Sul, Porto Alegre.

Almeida, J.A., 2017. Solos das pradarias mistas do sul do Brasil (Pampa Gaúcho). In: Curi, N., Ker, J.C., Novais, R.F., Vidal-Torrado, P., Schaefer, C.E.G.R. (Eds.), Pedologia - Solos dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 407–466.

Anghinoni, I., Vezzani, F.M., 2021. Systemic soil fertility as product of system self-organization resulting from management. Rev. Bras. Cienc. Solo. 45 https://doi.org/10.36783/18069657rbcs20210090.

Anghinoni, G., Anghinoni, F.B.G., Tormena, C.A., Braccini, A.L., Mendes, I.C., Zancanaro, L., Lal, R., 2021. Conservation agriculture strengthen sustainability of Brazilian grain production and food security. Land Use Policy 108, 105591. https://doi.org/10.1016/j.landusepol.2021.105591.

Araújo Filho, J.C., Ribeiro, M.R., Burgos, N., Marques, F.A., 2017. Solos da Caatinga. In: Curi, N., Ker, J.C., Novais, R.F., Vidal-Torrado, P., Schaefer, C.E.G.R. (Eds.), Pedologia - Solos dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 227–260.

Balota, E.L., Chaves, J.C.D., 2010. Enzymatic activity and mineralization of carbon and nitrogen in soil cultivated with coffee and green manures. Rev. Bras. Cienc. Solo. 34, 1573–1583. https://doi.org/10.1590/S0100-06832010000500010.

Balota, E.L., Kanashiro, M., Colozzi Filho, A., Andrade, D.S., Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Braz. J. Microbiol. 35, 300–306. https://doi.org/10.1590/S1517-83822004000300006.

Balota, E.L., Nogueira, M.A., Mendes, I.C., Hungria, M., Fagotti, D.S.L., Melo, G.M.P., Souza, R.C., Melo, W.J., 2013. Enzimas e seu papel na Qualidade do Solo. In: Araújo, A.P., Alves, B.J.R. (Eds.), Tópicos em Ciência do Solo - Volume VIII. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 222–271.

Balota, E.L., Calegari, A., Nakatani, A.S., Coyne, M.S., 2014. Benefits of winter cover crops and no-tillage for microbial parameters in a Brazilian Oxisol: a long-term study. Agric. Ecosyst. Environ. 197, 31–40. https://doi.org/10.1016/j.agee.2014.07.010.

Bandick, A.K., Dick, R.P., 1999. Field management effects on soil enzyme activities. Soil Biol. Biochem. 31, 1471–1479. https://doi.org/10.1016/S0038-0717(99)00051-6.

Barbosa, J.Z., Poggere, G., Silva, S.H.G., Mancini, M., Motta, A.C.V., Marques, J.J.G.S.M., Curi, N., 2021. National-scale spatial variations of soil magnetic susceptibility in Brazil. J. S. Am. Earth Sci. 108, 103191 https://doi.org/10.1016/j.jsames.2021.103191.

Barbosa, J.Z., Roberto, L.A., Hungria, M., Corrêa, R.S., Magri, E., Correia, T.D., 2022a. Meta-analysis of maize responses to *Azospirillum brasilense* inoculation in Brazil: benefits and lessons to improve inoculation efficiency. Appl. Soil Ecol. 170, 104276 https://doi.org/10.1016/j.apsoil.2021.104276.

Barbosa, J.Z., Poggere, G., Mancini, M., Silva, S.H.G., Motta, A.C.V., Marques, J.J.G.S.M., Curi, N., 2022b. National-scale spatial variations of soil phosphorus retention capacity in Brazil. Phys. Chem. Earth 128, 103271. https://doi.org/10.1016/j.pce.2022.103271.

Barcellos, M., Motta, A.C.V., Pauletti, V., Silva, J.C.P.M., Barbosa, J.Z., 2015. Atributos químicos de Latossolo sob plantio direto adubado com esterco de bovinos e fertilizantes minerais. Comun. Sci. 6, 263–273. https://doi.org/10.14295/cs.v6i3.527.

Barros, J.A., Medeiros, E.V., Costa, D.P., Duda, G.P., Lima, J.R.S., Santos, U.J., Antonino, A.C.D., Hammecker, C., 2020. Human disturbance affects enzyme activity, microbial biomass and organic carbon in tropical dry sub-humid pasture and forest soils. Arch. Agron. Soil Sci. 66, 458–472. https://doi.org/10.1080/03650340.2019.1622095.

Bobul'ská, L.E.N.K.A., Espindola, S.P., Coelho, M.A., Ferreira, A.S., 2021. Impact of land use on soil function and bacterial community in the Brazilian savanna. An. Acad. Bras. Cienc. 93 https://doi.org/10.1590/0001-3765202120201906.

Brookes, P.C., Landman, A., Pruden, G., Jenkinson, D.S., 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol. Biochem. 17, 837–842. https://doi.org/10.1016/0038-0717(85)90144-0.

Burns, R.G., DeForest, J.L., Marxsen, J., Sinsabaugh, R.L., Stromberger, M.E., Wallenstein, M.D., Weintraub, M.N., Zoppini, A., 2013. Soil enzymes in a changing environment: current knowledge and future directions. Soil Biol. Biochem. 58, 216–234. https://doi.org/10.1016/j.soilbio.2012.11.009.

Bustamante, M.M.C., Nardoto, G.B., Martinelli, L.A., 2004. Aspectos de ciclaje de nutrientes entre bosques amazónicos de terra-firme y sabanas tropicales (Cerrado brasileiro). In: Cabrera, H.M. (Ed.), Fisología ecológica en Plantas: mecanismos y respuestas a estrés en los ecosistemas. Ediciones Universitarias de Valparaiso, Valparaiso, pp. 189–206.

Caballero, C.B., Ruhoff, A., Biggs, T., 2022. Land use and land cover changes and their impacts on surface-atmosphere interactions in Brazil: a systematic review. Sci. Total Environ. 808, 152134 https://doi.org/10.1016/j.scitotenv.2021.152134.

Carlos, F.S., Schaffer, N., Marcolin, E., Fernandes, R.S., Mariot, R., Mazzurana, M., Roesh, L.F.W., Levandoski, B., Camargo, F.A.O., 2021. A long-term no-tillage system can increase enzymatic activity and maintain bacterial richness in paddy fields. Land Degrad. Dev. 32, 2257–2268. https://doi.org/10.1002/ldr.3896.

Carneiro, M.A.C., Souza, E.D.D., Reis, E.F.D., Pereira, H.S., Azevedo, W.R.D., 2009. Atributos físicos, químicos e biológicos de solo de cerrado sob diferentes sistemas de uso e manejo. Rev. Bras. Cienc. Solo. 33, 147–157. https://doi.org/10.1590/S0100-06832009000100016.

Carvalho, P.C.F., Anghinoni, I., Moraes, A., Souza, E.D., Sulc, R.M., Lang, C.R., Flores, J. P.C., Lopes, M.L.T., Silva, J.L.S., Conte, O., Wesp, C.L., Levien, R., Fontaneli, R.S., Bayer, C., 2010. Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems. Nutr. Cycl. Agroecosyst. 88, 259–273. https://doi.org/10.1007/s10705-010-9360-x.

Casida, L.E., Klein, D.A., Santoro, T., 1964. Soil dehydrogenase activity. Soil Sci. 98, 371–376.

Coelho, R.M., Rossi, M., Mattos, I.F.A., 2017. Solos da Mata Atlântica. In: Curi, N., Ker, J. C., Novais, R.F., Vidal-Torrado, P., Schaefer, C.E.G.R. (Eds.), Pedologia - Solos dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 261–302.

Cordeiro, C.F.S., Rodrigues, D.R., Rocha, C.H., Araujo, F.F., Echer, F.R., 2021. Glomalin and microbial activity affected by cover crops and nitrogen management in sandy soil with cotton cultivation. Appl. Soil Ecol. 167, 104026 https://doi.org/10.1016/j.apsoil.2021.104026.

Costa, M.P., Schoeneboom, J.C., Oliveira, S.A., Vinas, R.S., Medeiros, G.A., 2018. A socio-eco-efficiency analysis of integrated and non-integrated crop-livestock-forestry systems in the Brazilian Cerrado based on LCA. J. Clean. Prod. 171, 1460–1471. https://doi.org/10.1016/j.jclepro.2017.10.063.

Costa, D.P., Araujo, A.S.F., Pereira, A.P.A., Mendes, L.W., França, R.F., Silva, T.D.G.E., Oliveira, J.B., Araujo, J.S., Duda, G.P., Menezes, R.S.C., Medeiros, E.V., 2022. Forest-to-pasture conversion modifies the soil bacterial community in Brazilian dry forest Caatinga. Sci. Total Environ. 810, 151943 https://doi.org/10.1016/j.scitotenv.2021.151943.

Couto, E.G., Oliveira, V.A., Beirigo, R.M., Oliveira Junior, R.M., Nascimento, A.F., Vidal-Torrado, P., 2017. Solos do pantanal matogrossense. In: Curi, N., Ker, J.C., Novais, R. F., Vidal-Torrado, P., Schaefer, C.E.G.R. (Eds.), Pedologia - Solos dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 304–352.

Creamer, R.E., Barel, J.M., Bongiorno, G., Zwetsloot, M., 2022. The life of soils: integrating the who and how of multifunctionality. Soil Biol. Biochem. 166, 108561 https://doi.org/10.1016/j.soilbio.2022.108561.

Cunha, J.R., Freitas, R.D.C.A., Souza, D.J.D.A.T., Gualberto, A.V.S., Souza, H.A., Leite, L. F.C., 2021. Soil biological attributes in monoculture and integrated systems in the Cerrado region of Piauí State, Brazil. Acta Sci. Agron. 43, e51814. https://doi.org/10.4025/actasciagron.v43i1.51814.

Damian, J.M., Matos, E.S., Pedreira, B.C., Carvalho, P.C.F., Souza, A.J., Andreote, F.D., Premazzi, L.M., Cerri, C.E.P., 2021. Pastureland intensification and diversification in Brazil mediate soil bacterial community structure changes and soil C accumulation. Appl. Soil Ecol. 160, 103858 https://doi.org/10.1016/j.apsoil.2020.103858.

Didoné, E.J., Minella, J.P.G., Schneider, F.J.A., Londero, A.L., Lefevre, I., Evrard, O., 2019. Quantifying the impact of no-tillage on soil redistribution in a cultivated catchment of Southern Brazil (1964–2016) with $^{137}$Cs inventory measurements. Agric. Ecosyst. Environ. 284, 106588 https://doi.org/10.1016/j.agee.2019.106588.

Durrer, A., Gumiere, T., Zagatto, M.R.G., Feiler, H.P., Silva, A.M.M., Longaresi, R.H., Homma, S.K., Cardoso, E.J., 2021. Organic farming practices change the soil bacteria community, improving soil quality and maize crop yields. PeerJ. 9, e11985 https://doi.org/10.7717/peerj.11985.

Eivazi, F., Tabatabai, M.A., 1977. Phosphatases in soils. Soil Biol. Biochem. 9, 167–172. https://doi.org/10.1016/0038-0717(77)90070-0.

Eivazi, F., Tabatabai, M.A., 1988. Glucosidases and galactosidases in soils. Soil Biol. Biochem. 20, 601–606. https://doi.org/10.1016/0038-0717(88)90141-1.

EY Brasil/CropLife, 2021. Innovation Agrobussiness. https://croplifebrasil.org/publicacoes/innovation-in-agribusiness-and-training-of-brazilian-farmers-in-the-digital-age/ (accessed 25 March 2022).

FAOSTAT, 2020. Data. http://www.fao.org/faostat/en/#data (accessed 25 March 2022).

Feiler, H.P., 2020. Comunidade de fungos micorrízicos arbusculares em áreas de manejo de milho (*Zea mays* L.) orgânico, natural e convencional. https://doi.org/10.11606/D.11.2020.tde-18052020-121629 (accessed 25 March 2022).

Feltran-Barbieri, R., Féres, J.G., 2021. Degraded pastures in Brazil: improving livestock production and forest restoration. R. Soc. Open Sci. 8, 201854 https://doi.org/10.1098/rsos.201854.

Firmano, R.F., Colzato, M., Bossolani, J.W., Colnago, L.A., Martin-Neto, L., Alleoni, L.R. F., 2021. Long-term lime and phosphogypsum broadcast affects phosphorus cycling in a tropical Oxisol cultivated with soybean under no-till. Nutr. Cycl. Agroecosyst. 120, 307–324. https://doi.org/10.1007/s10705-021-10151-8.

Franco, A.D.J., Silva, A.P.V.D., Souza, A.B.S., Oliveira, R.L., Batista, É.R., Souza, E.D.D., Silva, A.O., Carneiro, M.A.C., 2020. Plant diversity in integrated crop-livestock systems increases the soil enzymatic activity in the short term. Pesqui. Agropecu. Trop. 50 https://doi.org/10.1590/1983-40632020v5064026.

Guedes, R.S., Alleoni, L.R.F., Correia, B.L., Alves, L.W.R., Ramos, S.J., Fernandes, A.R., 2020. Tillage systems and cover plants change organic fractions of phosphorus in

oxisol of eastern Amazonia. Bragantia. 79, 434–446. https://doi.org/10.1590/1678-4499.20200047.
Hungria, M., Barbosa, J.Z., Rondina, A.B.L., Nogueira, M.A., 2022. Improving maize sustainability with partial replacement of N fertilizers by inoculation with *Azospirillum brasilense*. Agron. J. 114, 2969–2980. https://doi.org/10.1002/agj2.21150.
Kandeler, E., Tscherko, D., Spiegel, H., 1999. Long-term monitoring of microbial biomass, N mineralisation and enzyme activities of a Chernozem under different tillage management. Biol. Fertil. Soils 28, 343–351. https://doi.org/10.1007/s003740050502.
Kaschuk, G., Alberton, O., Hungria, M., 2011. Quantifying effects of different agricultural land uses on soil microbial biomass and activity in Brazilian biomes: inferences to improve soil quality. Plant Soil 338, 467–481. https://doi.org/10.1007/s11104-010-0559-z.
Kulinska, D., Camargo, V.L.L., Drozdowicz, A., 1982. Enzyme-activities in Cerrado soils in Brazil. Pedobiologia. 24, 101–107.
Kuwano, B.H., Nogueira, M.A., Santos, C.A., Fagotti, D.S., Santos, M.B., Lescano, L.E., Andrade, D.S., Barbosa, G.M.C., Tavares-Filho, J., 2017. Application of landfill leachate improves wheat nutrition and yield but has minor effects on soil properties. J. Environ. Qual. 46, 153–159. https://doi.org/10.2134/jeq2016.02.0041.
Lanna, A.C., Silveira, P.M.D., Silva, M.B.D., Ferraresi, T.M., Kliemann, H.J., 2010. Atividade de urease no solo com feijoeiro influenciada pela cobertura vegetal e sistemas de plantio. Rev. Bras. Cienc. Solo. 34, 1933–1939. https://doi.org/10.1590/S0100-06832010000600018.
Leite, H.M.F., Calonego, J.C., Rosolem, C.A., Mendes, L.W., Moraes, L.N., Grotto, R.M.T., Araujo, F.F., Pereira, A.P.A., Melo, V.M.M., Araujo, A.S.F., 2021. Cover crops shape the soil bacterial community in a tropical soil under no-till. Appl. Soil Ecol. 168, 104166 https://doi.org/10.1016/j.apsoil.2021.104166.
Lopes, A.A.C., Sousa, D.M.G., Chaer, G.M., Reis Junior, F.B., Goedert, W.J., Mendes, I.C., 2013. Interpretation of microbial soil indicators as a function of crop yield and organic carbon. Soil Sci. Soc. Am. J. 77, 461–472. https://doi.org/10.2136/sssaj2012.0191.
Lopes, A.A.C., Sousa, D.M.G., Reis Junior, F.B., Mendes, I.C., 2015. Air-drying and long-term storage effects on β-glucosidase, acid phosphatase and arylsulfatase activities in a tropical savannah oxisol. Appl. Soil Ecol. 93, 68–77. https://doi.org/10.1016/j.apsoil.2015.04.001.
Lopes, A.A.C., Sousa, D.M.G., Reis Junior, F.B., Figueiredo, C.C., Malaquias, J.V., Souza, L.M., Mendes, I.C., 2018. Temporal variation and critical limits of microbial indicators in oxisols in the Cerrado, Brazil. Geoderma Reg. 12, 72–82. https://doi.org/10.1016/j.geodrs.2018.01.003.
Lopes, A.A.C., Bogiani, J.C., Figueiredo, C.C., Reis Junior, F.B., Sousa, D.M.G., Malaquias, J.V., Mendes, I.C., 2021. Enzyme activities in a sandy soil of Western Bahia under cotton production systems: short-term effects, temporal variability, and the FERTBIO sample concept. Braz. J. Microbiol. 52, 2193–2204. https://doi.org/10.1007/s42770-021-00606-z.
MapBiomas, 2020. MapBiomas. http://mapbiomas.org (accessed 25 March 2022).
Marafon, G., Barbosa, R.S., Lacerda, J.J.J., Martins, V., Costa, O.S., 2020. C and P pool restoration by a no-tillage system on Brazilian Cerrado Oxisol in Piauí State. Environ. Monit. Assess. 192 https://doi.org/10.1007/s10661-020-8221-6.
Margalef, O., Sardans, J., Fernández-Martínez, M., Molowny-Horas, R., Janssens, I.A., Ciais, P., Goll, D., Richter, A., Obersteiner, M., Asensio, D., Peñuelas, J., 2017. Global patterns of phosphatase activity in natural soils. Sci. Rep. 7, 1–13. https://doi.org/10.1038/s41598-017-01418-8.
Mariscal-Sancho, I., Ball, B., McKenzie, B., 2018. Influence of tillage practices, organic manures and extrinsic factors on β-glucosidase activity: the final step of cellulose hydrolysis. Soil Syst. 2, 21. https://doi.org/10.3390/soilsystems2020021.
Medeiros, E.V., Notaro, K.A., Barros, J.A., Moraes, W.S., Silva, A.O., Moreira, K.A., 2015. Absolute and specific enzymatic activities of sandy entisol from tropical dry forest, monoculture and intercropping areas. Soil Tillage Res. 145, 208–215. https://doi.org/10.1016/j.still.2014.09.013.
Melo, W., Pizauro-Junior, J., Kanesiro, M.A., Chelli, R., Leite, S.A., 1982. Efeito do método de irrigação sobre a atividade de amilase e hidrolase em um Latossolo Roxo cultivado com cenoura (*Daucus carota* L. cultivar Kuroda). Científica. 10, 41–48.
Mendes, I.C., Fernandes, M.F., Chaer, G.M., Reis Junior, F.B., 2012. Biological functioning of Brazilian Cerrado soils under different vegetation types. Plant Soil 359, 183–195. https://doi.org/10.1007/s11104-012-1195-6.
Mendes, I.C., Sousa, D.M.G., Reis Junior, F.B., Lopes, A.A.C., Souza, L.M., 2019a. Bioanálise de solo: aspectos teóricos e práticos. In: Severino, E.C., Moraes, M.F., Paula, A.M. (Eds.), Tópicos em Ciência do Solo. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 399–462.
Mendes, I.C., Ono, F.B., Oliveira, M.I., Silva, R.G., Kappes, C., Reis-Junior, F.B., Zancanaro, L., 2019c. Rotação de culturas, bioindicadores e saúde do solo. In: Kappes, C. (Ed.), Boletim de Pesquisa 2019/2020. Fundação MT, Rondonópolis, pp. 87–96.
Mendes, I.C., Sousa, D.M.G., Chaer, G.M., Reis Junior, F.B., Lopes, A.A.C., Dantas, O.D., Souza, L.M., 2021a. Soil bioanalysis: a simple and effective tool to access and interpret soil health. In: Proceedings of the Global Symposium on Soil Biodiversity 2021. Rome, pp. 256–261. https://doi.org/10.4060/cb7374en.
Mendes, I.C., Sousa, D.M.G., Dantas, O.D., Lopes, A.A.C., Reis Junior, F.B., Oliveira, M.I.L., Chaer, G.M., 2021b. Soil quality and grain yield: a win-win combination in clayey tropical Oxisols. Geoderma. 388 https://doi.org/10.1016/j.geoderma.2020.114880 (114880-10).
Mendes, I.C., Souza, L.M., Sousa, D.M.G., Lopes, A.A.C., Reis Junior, F.B., Lacerda, M.P.C., Malaquias, J.V., 2019b. Critical limits for microbial indicators in tropical Oxisols at post-harvest: the FERTBIO soil sample concept. Appl. Soil Ecol. 139, 85–93. https://doi.org/10.1016/j.apsoil.2019.02.025.
Mirzavand, J., Asadi-Rahmani, H., Moradi-Talebbeigi, R., 2022. Biological indicators of soil quality under conventional, reduced, and no-tillage systems. Arch. Agron. Soil Sci. 68, 311–324. https://doi.org/10.1080/03650340.2020.1832656.
Mori, T., 2022. Greater impacts of phosphorus fertilization on soil phosphatase activity in tropical forests than in non-tropical natural terrestrial ecosystems: a meta-analysis. Pedobiologia. 91, 150808 https://doi.org/10.1016/j.pedobi.2022.150808.
Nacata, G., 2021. Práticas alternativas de manejo sobre a qualidade do solo e de abacateiros\'Hass\'. Escola Superior de Agricultura Luiz de Queiroz, Piracicaba. https://doi.org/10.11606/T.11.2021.tde-15062021-160953.
Naves, A.P., Silva, A.O., Barbosa, M.V., Pinto, F.A., Santos, J.V., Saggin Junior, O.J., Guimarães, P.T.G., Carneiro, M.A.C., 2020. Biochemical attributes of a Oxisol submitted to high doses of gypsum in the coffee culture. Coffee 15, e151756. https://doi.org/10.25186/.v15i.1756.
Nivelle, E., Verzeaux, J., Habbib, H., Kuzyakov, Y., Decocq, G., Roger, D., Lacoux, J., Duclercq, J., Spicher, F., Nava-Saucedo, J.E., Catterou, M., Dubois, F., Tetu, T., 2016. Functional response of soil microbial communities to tillage, cover crops and nitrogen fertilization. Appl. Soil Ecol. 108, 147–155. https://doi.org/10.1016/j.apsoil.2016.08.004.
Nogueira, M.A., Albino, U.B., Brandao-Junior, O., Braun, G., Cruz, M.F., Dias, B.A., Duarte, R.T.D., Gioppo, N.M.R., Menna, P., Orlandi, J.M., Raiman, M.P., Rampazo, L.G.L., Santos, M.A., Silva, M.E.Z., Vieria, F.P., Torezan, J.M.D., Hungria, M., Andrade, G., 2006. Promising indicators for assessment of agroecosystems alteration among natural, reforested and agricultural land use in southern Brazil. Agric. Ecosyst. Environ. 115, 237–247. https://doi.org/10.1016/j.agee.2006.01.008.
Notaro, K.A., Medeiros, E.V.D., Duda, G.P., Moreira, K.A., Barros, J.A.D., Santos, U.J.D., Lima, J.R.S., Moraes, W.D.S., 2018. Enzymatic activity, microbial biomass, and organic carbon of Entisols from Brazilian tropical dry forest and annual and perennial crops. Chil. J. Agric. Res. 78, 68–77. https://doi.org/10.4067/S0718-58392018000100068.
Oliveira, V.A., Jacomine, P.K.T., Couto, E.G., 2017. Solos do bioma Cerrado. In: Curi, N., Ker, J.C., Novais, R.F., Vidal-Torrado, P., Schaefer, C.E.G.R. (Eds.), Pedologia - Solos dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 178–226.
Parra, J.R.P., 2014. Biological control in Brazil: an overview. Sci. Agric. 71, 345–355. https://doi.org/10.1590/0103-9016-2014-0167.
Passinato, J.H., Amado, T.J., Kassam, A., Acosta, J.A., Amaral, L.D.P., 2021. Soil health check-up of conservation agriculture farming systems in Brazil. Agronomy. 11, 2410. https://doi.org/10.3390/agronomy11122410.
Paul, R., Datta, S.C., Bera, T., Math, M.K., Bhattacharyya, R., Dahuja, A., 2022. Interaction of phosphatase with soil nanoclays: kinetics, thermodynamics and activities. Geoderma. 409, 115654 https://doi.org/10.1016/j.geoderma.2021.115654.
Pedrotti, A., Ferreira, E.P.B., Assunção, S.J.R., de Araújo Filho, R.N., Gomes Filho, R.R., Oliveira, O.S., Holanda, F.S.R., 2018. Biological activity as an indicator of soil quality under different cultivation systems in Northeastern Brazil. J. Exp. Agric. Int. 22, 1–13.
Peixoto, R.S., Chaer, G.M., Franco, N., Reis Junior, F.B., Mendes, I.C., Rosado, A.S., 2010. A decade of land use contributes to changes in the chemistry, biochemistry and bacterial community structures of soils in the Cerrado. Antonie Leeuwenhoek. 98, 403–413. https://doi.org/10.1007/s10482-010-9454-0.
Pelissaro, H., Zanella, M., Santos, S., Cardoso, E., Brasil, M., 2020. Atributos microbiológicos do solo como indicadores de conservação das pastagens nativas do Pantanal. In: Silva-Matos, R.R.S., Machado, F.G.A., Oliveira Neto, E.D. (Eds.), O solo na mitigação e/ou resolução de problemas ambientais. Atena Editora, Ponta Grossa, pp. 1–13 (doi:10.22533/at.ed.591201901).
Peng, S., Liu, W., Xu, G., Pei, X., Millerick, K., Duan, B., 2021. A meta-analysis of soil microbial and physicochemical properties following native forest conversion. Catena. 204, 105447 https://doi.org/10.1016/j.catena.2021.105447.
Pessoa-Filho, M., Barreto, C.C., Reis Junior, F.B., Fragoso, R.R., Costa, F.S., Mendes, I.C., Andrade, L.R.M., 2015. Microbiological functioning, diversity, and structure of bacterial communities in ultramafic soils from a tropical savanna. Antonie Leeuwenhoek. 107, 935–949. https://doi.org/10.1007/s10482-015-0386-6.
Pires, G.C., Denardin, L.G.O, Silva, L.S., Freitas, C.M., Gonçalves, E.C., Camargo, T.A., Bremm, C., Carvalho, P.C.F., Souza, E.D., 2022. System fertilization increases soybean yield through soil quality improvements in integrated crop-livestock system in tropical soils. J. Soil Sci. Plant Nutr. 22, 4487–4495. https://doi.org/10.1007/s42729-022-01050-0.
Poggere, G., Santana, M.J.B., Barbosa, J.Z., Corrêa, R.S., Melo, L.C.A., 2022. A data synthesis on the biochar properties and implications for air, soil, and water quality in Brazil. Environ. Qual. Manag. 32, 27–41. https://doi.org/10.1002/tqem.21875.
Polidoro, J.C., Freitas, P.L., Hernani, L.C., Anjos, L.H.C.D., Rodrigues, R.D.A.R., Cesário, F.V., Andrade, A.G., Ribeiro, J.L., 2021. Potential impact of plans and policies based on the principles of conservation agriculture on the control of soil erosion in Brazil. Land Degrad. Dev. 32, 3457–3468. https://doi.org/10.1002/ldr.3876.
Portilho, I.I.R., Scorza Júnior, R.P., Salton, J.C., Mendes, I.D.C., Mercante, F.M., 2015. Persistência de inseticidas e parâmetros microbiológicos em solo sob sistemas de manejo. Cienc. Rural. 45, 22–28. https://doi.org/10.1590/0103-8478cr20131328.
Resende, M., Curi, N., Poggere, G.C., Barbosa, J.Z., Pozza, A.A.A., 2019. Pedologia, Fertilidade, Água e Planta: Inter-relações e aplicações, first ed. Editora UFLA, Lavras.
Ribeiro, G.H.D.S., 2012. Qualidade biológica de solos de cerrado em áreas degradadas e sob diferentes manejos de cana-de-açúcar. Universidade Católica de Brasília, Brasília.
Roscoe, R., Mercante, F.M., Mendes, I.C., Reis-Junior, F.B., Santos, J.C.F., Hungria, M., 2006. Biomassa microbiana do solo: fração mais ativa da matéria orgânica. In: Roscoe, R., Mercante, F.M., Salton, J.C. (Eds.), Dinâmica da Matéria Orgânica do

Solo em Sistemas conservacionistas – Modelagem Matemática e Métodos Auxiliares. Embrapa Agropecuária Oeste, Dourados, pp. 163–200.
Santos, D.C.R., 2020. Fluxos de $N_2O$ e atributos do solo em sistemas integrados de produção de longa duração sob dois níveis de P e K. Universidade de Brasília, Brasília.
Schaefer, C.E.G.R., Lima, H.N., Teixeira, W.G., Vale Jr., J.F., Souza, K.W., Corrêia, G.R., Mendonça, B.A.F., Amaral, E.F., Campos, M.C.C., Ruivo, M.L., 2017. Solos da região amazônica. In: Curi, N., Ker, J.C., Novais, R.F., Vidal-Torrado, P., Schaefer, C.E.G.R. (Eds.), Pedologia - Solos dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa, pp. 111–175.
Schinner, F., Von Mersi, W., 1990. Xylanase-, CM-cellulase-and invertase activity in soil: an improved method. Soil Biol. Biochem. 22, 511–515. https://doi.org/10.1016/0038-0717(90)90187-5.
Silva, É.O., de Medeiros, E.V., Duda, G.P., Lira Junior, M.A., Brossard, M., de Oliveira, J. B., Santos, U.J., Hammecker, C., 2019. Seasonal effect of land use type on soil absolute and specific enzyme activities in a Brazilian semi-arid region. Catena. 172, 397–407. https://doi.org/10.1016/j.catena.2018.09.007.
Simon, C.A., Lima, S.F., Cordeiro, M.S., Secco, V.A., Nacata, G., Silva, A.M.M., Simon, C. C., Brasil, M.S., 2019. Cover crops as modifying agents of microbiological soil attribute. Aust. J. Crop. Sci. 13, 1578–1585. https://doi.org/10.21475/ajcs.19.13.10.p1723.
Sinsabaugh, R.L., Lauber, C.L., Weintraub, M.N., Ahmed, B., Allison, S.D., Crenshaw, C., Contosta, A.R., Cusack, D., Frey, S., Gallo, M.E., Gartner, T.B., Hobbie, S.E., Holland, K., Keeler, B.L., Powers, J.S., Stursova, M., Takacs-Vesbach, C., Waldrop, M. P., Wallenstein, M.D., Zak, D.R., Zeglin, L.H., 2008. Stoichiometry of soil enzyme activity at global scale. Ecol. Lett. 11, 1252–1264. https://doi.org/10.1111/j.1461-0248.2008.01245.x.
Skorupa, L.A., Manzatto, C.V., 2019. Avaliação da adoção de sistemas de integração lavoura-pecuária-floresta (ILPF) no Brasil. In: Skorupa, L.A., Manzatto, C.V. (Eds.), Sistemas de integração lavoura-pecuária-floresta no Brasil: estratégias regionais de transferência de tecnologia, avaliação da adoção e de impactos. Embrapa, Brasília, pp. 340–379.
Soares, D.D.A., 2021. Dinâmica da matéria orgânica e qualidade do solo em sistemas de produção agropecuários. Universidade Estadual Paulista, Ilha Solteira.
Sobucki, L., Ramos, R.F., Meireles, L.A., Antoniolli, Z.I., Jacques, R.J.S., 2021. Contribution of enzymes to soil quality and the evolution of research in Brazil. Rev. Bras. Cienc. Solo. 45 https://doi.org/10.36783/18069657rbcs20210109.
Sousa, H., Correa, A.R., Silva, B.D.M., Oliveira, S.D.S., Campos, D.T.D.S., Wruck, F.J., 2020. Dynamics of soil microbiological attributes in integrated crop-livestock systems in the cerrado-amazonônia ecotone. Rev. Caatinga. 33, 09–20. https://doi.org/10.1590/1983-21252020v33n102rc.
Souza, R.C., Mendes, I.C., Reis-Junior, F.B., Carvalho, F.M., Nogueira, M.A., Vasconcelos, A.T.R., Vicente, V.A., Hungria, M., 2016. Shifts in taxonomic and functional microbial diversity with agriculture: how fragile is the Brazilian Cerrado? BMC Microbiol. 16, 1–15. https://doi.org/10.1186/s12866-016-0657-z.
Spiers, G.A., McGill, W.B., 1979. Effects of phosphorus addition and energy supply on acid phosphatase production and activity in soils. Soil Biol. Biochem. 11, 3–8. https://doi.org/10.1016/0038-0717(79)90110-X.
Spohn, M., Kuzyakov, Y., 2013. Distribution of microbial-and root-derived phosphatase activities in the rhizosphere depending on P availability and C allocation–coupling soil zymography with $^{14}C$ imaging. Soil Biol. Biochem. 67, 106–113. https://doi.org/10.1016/j.soilbio.2013.08.015.
Tabatabai, M.A., 1994. Soil enzymes. In: Weaver, R.W., Angle, S., Bottomley, P., Bezdicek, D., Smith, S., Tabatabai, A., Wollum, A. (Eds.), Methods of Soil Analysis: Part 2. Microbiological and Biochemical Properties. Soil Science Society of America, Madison, pp. 775–833. https://doi.org/10.2136/sssabookser5.2.c37.
Tabatabai, M.A., Bremner, J.M., 1970. Arylsulfatase activity of soils. Soil Sci. Soc. Am. J. 34, 225–229. https://doi.org/10.2136/sssaj1970.03615995003400020016x.
Tabatabai, M.A., Bremner, J.M., 1972. Assay of urease activity in soils. Soil Biol. Biochem. 4, 479–487. https://doi.org/10.1016/0038-0717(72)90064-8.
Talbot, J.M., Bruns, T.D., Taylor, J.W., Smith, D.P., Branco, S., Glassman, S.I., Erlandson, G., Vilgalys, R., Liao, H., Smith, M.E., Peay, K.G., 2014. Endemism and functional convergence across the North American soil mycobiome. Proc. Natl. Acad. Sci. U. S. A. 111, 6341–6346. https://doi.org/10.1073/pnas.1402584111.
Tan, X., Xie, B., Wang, J., He, W., Wang, X., Wei, G., 2014. County-scale spatial distribution of soil enzyme activities and enzyme activity indices in agricultural land: implications for soil quality assessment. Sci. World J. 2014, 535768 https://doi.org/10.1155/2014/535768.
Tenelli, S., Bordonal, R.O., Barbosa, L.C., Carvalho, J.L.N., 2019. Can reduced tillage sustain sugarcane yield and soil carbon if straw is removed? Bioenergy Res. 12, 764–777. https://doi.org/10.1007/s12155-019-09996-3.
Thomaz, E., Antoneli, V., 2022. Long-term soil quality decline due to the conventional tobacco tillage in southern Brazil. Arch. Agron. Soil Sci. 68 https://doi.org/10.1080/03650340.2020.1852550.
Torres, C.M., Pinheiro, A.D.S., Hungria, L.C., El-Husny, J.C., Sacramento, P.P., Andrade, I.P., 2020. Inorganic nitrogen fractions in soil under different uses and management systems in the Brazilian eastern Amazon. J. Agric. Stud. 8, 32–43. https://doi.org/10.5296/jas.v8i4.17080.
Valani, G.P., Martini, A.F., Silva, L.F.S., Bovi, R.C., Cooper, M., 2021. Soil quality assessments in integrated crop–livestock–forest systems: a review. Soil Use Manag. 37, 22–36. https://doi.org/10.1111/sum.12667.
Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703–707. https://doi.org/10.1016/0038-0717(87)90052-6.
Vilela, E.F., Callegaro, G.M., Fernandes, G.W., 2019. Biomas e agricultura: oportunidades e desafios. Vertente, Rio de Janeiro.
Vinhal-Freitas, I.C., Corrêa, G.F., Wendling, B., Bobuľská, L., Ferreira, A.S., 2017. Soil textural class plays a major role in evaluating the effects of land use on soil quality indicators. Ecol. Indic. 74, 182–190. https://doi.org/10.1016/j.ecolind.2016.11.020.
Wallenstein, M.D., Burns, R.G., 2011. Ecology of extracellular enzyme activities and organic matter degradation in soil: A complex community-driven process. In: Dick, R.P. (Ed.), Methods of Soil Enzymology. Soil Science Society of America, Madison, pp. 35–56. https://doi.org/10.2136/sssabookser9.c2.
Zago, L.M.S., Ramalho, W.P., Caramori, S., 2019. Does crop-livestock-forest systems contribute to soil quality in Brazilian savannas? Floresta e Ambient. 26 https://doi.org/10.1590/2179-8087.034318.
Zhao, Z., Jiang, Y., Mi, T., Ling, W., Huang, Q., Xia, L., 2012. Effects of addition sequence and pH of oxalate on the adsorption and activity of acid phosphatase on soil colloids and minerals. Commun. Soil Sci. Plant Anal. 43, 1436–1448. https://doi.org/10.1080/00103624.2012.670343.
Zheng, H., Liu, Y., Zhang, J., Chen, Y., Yang, L., Li, H., Wang, L., 2018. Factors influencing soil enzyme activity in China's forest ecosystems. Plant Ecol. 219, 31–44. https://doi.org/10.1007/s11258-017-0775-1.
Zuber, S.M., Villamil, M.B., 2016. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. Soil Biol. Biochem. 97, 176–187. https://doi.org/10.1016/j.soilbio.2016.03.011.